Increasing Drought Resilience of the Port-Hinterland System

A Case Study on the Rhine River.

Transport, Infrastructure and Logistics

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Summary

Future demand for container transport is expected to grow in the upcoming years. As climate is changing, the European Commission aims to shift 75% of the road freight transport to other, more sustainable transport modalities. As a result, inland waterway transport is being highly stimulated. At the same time, climate changes increase the chance of drought periods, which affect the inland waterway transportation system.

One promising strategy to increase drought resilience is the strategic establishment of new hubs or the extension of existing terminals to facilitate modality shifts. However, most research in the field of modal shift and network resilience focused on road or rail transport as the main transport modality, while research considering waterborne transport as the main modality is still limited. This research aims to fill this gap by investigating how the drought resilience of the port-hinterland system can be enhanced by the strategic establishment of transport hubs or extension of existing terminals in response to low water levels. This research aims to contribute to the goals of the European Commission to increase the reliability of the inland waterborne transport network to shift part of the market share of road freight transport to inland waterway transport. This research focuses on the most important inland waterway of Europe: the Rhine river. Establishment of hubs can be most beneficial when located before a bottleneck. The bottlenecks considered in this research are Druten, Duisburg, and Kaub.

The study is based on three different methodological pillars. First, data analysis was conducted. For this data analysis, different datasets have been used to analyze how the amount of transported cargo past Lobith changes over time. These variations have been linked to water discharge levels. The data analysis gave insights in how water discharge and actual water levels are related, which was used to create input data for the mathematical model. The data analysis gave insights into how the loading factor of different vessel types changes as a result of dropping water discharge levels, and it showed how the composition of the vessels used for transport changes. The data analysis was used to better understand how low water discharge affects inland waterway transport. These insights were used for the mathematical model. This model aims to minimize the total costs for transporting a predefined set of shipments from the origin to the corresponding destination using multi-modal transport. This model incorporates constraints that the terminal capacities cannot be exceeded while transshipping cargo. It includes constraints that ensure that the vessel draught does not exceed the available draught of a certain section in the river, which is affected by the loading factor of the vessel. It also includes hub selection and selection of existing terminals to extend. This model was used to simulate the transport of the shipments under normal river discharge conditions. The total costs, CO_2-equivalent emissions and the terminal capacity utilization of the terminals selected for transshipments were extracted as a benchmark for the results of the scenarios. The model served as input for the scenario-based analysis. In the scenario-based analysis, different scenarios, based on the river discharge and the available rail freight capacity, were constructed. In each scenario, the same performance indicators were extracted. The results of the different scenarios were compared against each other to analyze the impact of lowering water discharge levels on the existing network, the impact of the establishment of hubs in response to lower water discharge levels, and the impact of increasing the available rail freight capacity when keeping the river discharge level constant.

From the results, it can be concluded that investments in infrastructure is essential to increase the drought resilience of the port-hinterland transportation system of the Rhine river. Expanding the rail infrastructure contributes to a slight reduction of the total costs of transport of the shipments when river discharge decreases. Establishment of hubs reduces the total transport costs even further. Establishment of hubs is not only beneficial for a reduction of the total costs but also reduces the CO_2-equivalent emissions of the transport. It allows more cargo to be transported over greater distances by waterborne transport when river discharge drops. In the most extreme river discharge scenario, the transport performance of vessels does not change significantly with the establishment of transport hubs. However, in that case, the establishment of hubs still positively affects the total costs by allowing transport to be

transported by rail.

It was found that the location of hubs, the accessibility of rail infrastructure, and the capacity of the hubs are important for the selection of hubs to establish from a cost minimization perspective. Accessibility to rail infrastructure is only important if the final destination of the shipments that are transshipped in a terminal is far enough to make transport by rail economically viable. Hubs have to be located before bottlenecks, but allocation of shipments to a certain terminal and or hub is affected by the other terminals and hubs and their characteristics in the same region.

This research gives valueble insights for policymakers and transport authorities by providing a framework for evaluating trade-offs about whether new transshipment terminals have to be established and where they can contribute best to minimizing the total costs. Policymakers and transport authorities can use the results of this research to emphasize the relevance of increasing the drought resilience. The model can be used for other port-hinterland systems as well. For further research, it is recommended to extend the model by including hinterland-port transport, analyze the effects of hub establishment in non-drought periods, and investigate bottlenecks not only on the depth of the fairways but also on the width of the fairways.

Contents

1 Introduction

1.1. Research context

The transportation sector is one of the main sectors strongly contributing to the CO_2 emissions. The Dutch transport sector emitted 25 billion CO_2-equivalent units in 2023 (Centraal Bureau voor de Statistiek, n.d.-b). In the coming years, demand for transport is expected to increase substantially, which can result in more emissions (De Nederlandsche Bank, 2024).

The European Commission agreed on the European Green Deal, which has set the target of shifting 75% of road freight transport over long distances to more sustainable transport modalities, such as inland waterway transport (IWT) and rail (European Commission, 2021). As a result, IWT is increasingly being promoted due to its lower greenhouse gas emissions. Modal shift to IWT also has the potential to relieve already congested transport corridors (Inland Navigation Europe, n.d.; Zhou et al., 2024). The inland waterways have sufficient free space left to shift inland container transport to the waterways.

The Rotterdam–Limburg corridor serves as a successful example of this modal shift (Port of Rotterdam, 2024). A recent initiative by the Port of Rotterdam demonstrated that transferring 30% of road freight to rail and 70% to inland waterways led to a reduction of 7.7 million tons of CO_2 emissions (Port of Rotterdam, 2024). This illustrates the strategic importance of IWT in achieving both logistical efficiency and climate objectives.

However, the increasing reliance on IWT introduces new vulnerabilities, particularly in the context of climate change. Climate change causes, among others, an increase in the chance of drought periods which will occur more often in the future (Kennisportaal Klimaatadaptatie, n.d.). Climate change causes both rising water levels and droughts. Drought periods have larger impact on IWT, since these periods last longer than flood periods. Potential disruptions and long recovery times in freight transportation can have a significant impact on both society and the economy which increases the need to look into how the transport network can be prepared for more or longer drought periods. (Zhou et al., 2024).
Drought periods cause low water levels, which are a result of low water discharge. Water discharge is the rate at which water flows past a measurement point. Discharge is estimated based on water depth and flow velocity (Mihel et al., 2024). Increased discharge rates often result in increased river depth, indicating higher water levels. Conversely, decreased discharge rates may result in shallower river depths.
Periods of drought can lead to critically low water levels in rivers like the Rhine, which forces vessels to sail carrying less loading and decrease the sailing speed (Gerritse, 2023). As a result of strong capacity reduction, costs for transport increase. This is not only due to low water surcharges but also because less cost-efficient modalities have to be used for transport. Supply chains are disrupted. If nothing is done to increase the drought resilience of the port-hinterland system, between 7% and 20% of the annual container throughput will be lost by 2050 (Bedoya-Maya et al., 2024).

The dry summer of 2018 showed that low water levels resulted in an increase of container transport by road (Calderón-Rivera et al., 2024a). This increase in road transport captured a part of the market share that used to be of inland waterway transport (Calderón-Rivera et al., 2024a; European Commission et al., 2023). The inland transportation sector has not fully recovered yet from these losses in market share. The IWT sector faces demand fluctuations more often. These fluctuations are a result of various factors. An investigation on trends has shown that, between 2018 and 2022, a series of negative events affected container transport on the Rhine (European Commission et al., 2023). Low water periods in 2018 and 2022 caused cargo losses and losses in modal share in the following years. In 2019, new tariffs in world trade were introduced that negatively impacted both seaborne container transport as well as inland container transport. The Covid pandemic in 2020 and inflation in 2021 had an impact on container transport. In 2022 the conflict between Russia and Ukraine broke out, which increased inflation and disrupted world trade. In addition to these events, there was congestion in seaports. In 2021, the mode share of IWT is estimated at 5.6%, which is much smaller compared to rail and road transport, of which the market share is estimated at 17% and 77.4% respectively (CCNR, n.d.).

Although these factors can affect demand for IWT, the future demand is expected to grow. However, the climate is expected to also change in the future. These climate changes cause more and longer drought periods. The inland waterway transportation system needs to become more resilient against climate change. Resilience can be defined as "the quality of being able to return quickly to a previous good condition after problems" (Cambridge Dictionary, n.d). As summers get drier, water levels become lower and the fairways get narrower (Ministerie van Infrastructuur en Waterstaat, 2025). Longer and more frequent periods of low water levels will likely occur, which will be noticeable in the transport prices (Bedoya-Maya et al., 2024). In terms of available river depth and available terminal capacity in a region, Nijmegen, Duisburg and Kaub are identified as bottlenecks for the Rhine river (Van der Plas, 2024). Given both the low water levels and shallower fairways, it is important to adapt the inland waterway transport system to climate change. This can be done in different ways. Shipping companies can change the composition of the fleet (Vinke et al., 2024). To transport the same amount of cargo, the number of trips increases because of the reduced effective capacity. The maximum capacity utilization of a vessel is affected by the available water level. The loading of a vessel affects the vessel draught. Reduced effective loading capacity requires more vessels in order to transport the same amount of cargo over the river compared to normal water levels. More vessels increase the density of vessels on the river. With lowering water levels, the fairways narrow. The narrowed fairways increase the density of the vessels on the river even further (Ministerie van Infrastructuur en Waterstaat, 2025).

Changing the fleet also requires transshipment facilities. Terminal owners can establish additional facilities or extend existing facilities to transship cargo when the available draught is not sufficient for a vessel to continue with the same loading rate. In this research, these facilities are called 'terminals' or 'hubs'. Both terminals and hubs offer the same facilities. These facilities can be defined as a location that offers transshipment and sorting facilities in many-to-many distribution systems (Alumur & Kara, 2008). In this research, terminals refers to the existing terminals and hubs refers to the potential new terminals.

1.2. Research problem

To relieve the congested road and rail networks, and to contribute to the European Green Deal, freight transport is promoted to be transported by inland waterway transport. However, the inland waterway transportation system is still highly vulnerable to the impacts of droughts as a result of climate change. To increase the drought resilience of an inland waterway, it is known that transport hubs can positively affect the network performance under drought conditions. However, there is insufficient understanding of the exact impact on the drought resilience of an inland waterway system. According to Alumur and Kara (2008), hub location and allocation decisions have to be considered together when designing hub networks because locations affect allocations and allocations affect locations. Without adaptation, bottlenecks can lead to substantial capacity losses. This emphasizes the need to investigate how transport hubs increase the drought resilience of the port-hinterland system.

To investigate this, this research will focus on the main waterway of Europe: the Rhine river. The Rhine river consists of two sections: the lower Rhine Delta, which is the Rhine river from the Dutch/German border downstream, and the traditional Rhine, which is the Rhine from the basin to the Dutch/German border. In the lower Rhine delta, 13.1% of all inland waterway transport consists of container transport. In the traditional Rhine, this equals 8.8% (European Commission et al., 2023). There is a high transport intensity on the lower Rhine because of the dense network of chemical hubs and container terminals, the important industrial hub in Germany and high fairway depths (European Commission et al., 2023).

With the expected increase in demand and decreasing water levels in the future, it is important tot gain better understanding in how the current inland transportation system is affected by lowering water levels and how new hubs or extending existing terminals affect the inland transportation system in case of low water levels.

1.3. Research objective and scope

Given the desires for a growing market share of IWT for sustainable freight transport and the drought-related challenges for IWT, it is essential to examine how well the IWT system can withstand and adapt to drought-related disruptions. The goal of this research is to enhance the drought resilience of multi-modal port-hinterland container transport system from Rotterdam to the German hinterland with the focus on inland navigation over the Rhine river.

This research focuses on container transport over the Rhine river. More specifically, it focuses on container transport from Rotterdam to the German hinterland. The research includes both existing terminals with direct access to the Port of Rotterdam, and considers potential hubs based on the lists identified in previous research (Van der Plas, 2024). The list of potential hubs is adapted for this research but the locations of all hubs and terminals included is predetermined. Besides hub establishment, some existing terminals have sufficient empty space located around the terminal, which creates the possibility for terminal extension. This is also considered in the research. The research includes different RWS vessel types (M2, M4, M6 and M8) and modal shift to truck and train. The characteristics of the vessels like capacity, empty draught and loaded draught and the vehicle capacities of trucks and trains are known. The relation for each vessel type between the loading factor and the vessel draught is pre-determined and the available draught in each section of the river is included for different water discharge levels. The model allows for transshipment in the terminals and established hubs to train and/or truck, depending on the access to rail infrastructure. For river discharge scenarios, predictions have been used on the Agreed Low River discharge levels of 2050 and 2100. For the scenarios, changes in the capacity of rail infrastructure are also considered.

1.4. Research gap

Similar to the case study on the Rotterdam-Limburg corridor, most previous research mainly focuses on the effects of modal shifts for freight transport from road to waterborne transport and rail. Previous research also focuses on the shift from rail to road transport. However, research on modal shift for freight transport from inland waterway transport to road or rail remains limited. Considering the inland waterway as the main modality of transport is useful to investigate the possibilities to increase the drought resilience of the system. Research with a focus from this perspective is still limited.

Although it is known that container terminals before bottlenecks in the river contribute to improving the drought resilience of the inland waterway transportation system, knowledge remains limited on what the characteristics of these terminals should be, where they should be located, and how they affect the transportation system. From this perspective, it is crucial to gain insights into how the transportation system is affected by the establishment of new hubs or the extension of existing terminals in case of low river discharge scenarios.

1.5. Research questions

The main research question can be formulated as follows:

How can the resilience of the port-hinterland system for container transport along the Rhine river, from Rotterdam to Germany, be enhanced through strategic establishment of modal shift hubs in response to low water levels?

In order to find answers to the main research question, the following sub-questions can be formulated:

1. How do low water levels affect the capacity of inland waterways?
2. How can the locations of transport hubs be strategically selected to facilitate modal shift more efficiently in drought periods?

3. How does the establishment of strategic modal shift locations affect the shipping costs and the CO_2-equivalent emissions of the transport in response to lowering river discharge levels?
4. What trade-offs must policymakers consider when deciding whether and where to invest in new transshipment infrastructure?

1.6. Research method

To approach the research goal, the performance of the port-hinterland system will be analyzed in different scenarios with fluctuating river discharge levels and rail capacity fluctuations. To analyze the impact of the establishment of new hubs, in each scenario, the network performance will be conducted based on the existing terminals only and based on the network with established hubs. The impact of hub establishment will be analyzed by comparing the two cases. In this research, three methodology pillars will be used.

First, data analysis will be conducted on both data of river discharge levels measured at Lobith and transport statistics in the same period of time. The data analysis will be used to analyze how low water levels affect the amount of cargo transported over inland waterways. This analysis contributes to the input for the mathematical optimization model by defining a list of shipments that have to be routed through the network.
A mathematical optimization model will be developed focusing on the total cost minimization of the transport. In this study, the transport system will be approached from a holistic perspective. This means that the total costs, consisting of fixed capital vehicle costs, variable transport costs, transshipment costs, and time equivalent (daily) hub establishment costs are minimized while considering multi-modal transport given the available draught in the river, and transshipments in terminals based on access to infrastructure and considering the terminal capacity. For routing the shipments, the vessels can be loaded up to the effective capacity so that the vessel's draught does not exceed the available draught. The model can allow for hub establishment and terminal extension. This is useful for analyzing the impact of investing in new transshipment infrastructure on the total cost and the way shipments are routed through the network, which will be analyzed in the scenario-based analysis. For the base model, under normal river discharge conditions, the performance indicators total cost, CO_2-equivalent emissions of the transport, and the terminal utilization for modality shifts will be extracted.
The mathematical model will form the base for the scenario-based analysis. The scenarios are based on future river discharge levels and availability of rail capacity. The results of the different scenarios in the analysis will be compared against each other to find answers on what trade-offs must be considered when deciding on where to invest in new transshipment infrastructure. These steps are needed to gain insights into how the IWT system is affected by lowering water discharge levels, how strategic establishment contributes to cost minimization and what the impact is of expanding rail infrastructure in the port-hinterland system of container transport from Rotterdam to the German hinterland.

1.7. Structure

The structure of the report is as follows. Chapter 2 will give an overview of the existing literature and related models. Chapter 3 will give a general overview of the methodologies used in this research and how the different methodologies will build upon each other. Chapter 4 will describe the data used in this research, the pre-processing, and the data analysis with results. In both Chapters 2 and 4, sub-question 1 about the effect of low water levels on the capacity of inland waterways will be addressed. Chapter 5 will describe the problem and network in more depth and will provide the mathematical model. Chapter 6 describes the results of the base model, where cargo is transported through the network under normal river discharge conditions, and describes the sensitivity of the model. Chapter 7 defines the scenarios used in this research. It also describes the design of the network selected when hubs are being established. Then, the results of each scenario are described and analyzed. Sub-question 2 is addressed in both Chapters 5 and 7. Sub-questions 3 and 4 are addressed in Chapters 6 and 7 based on the results of the base model and the scenario-based analysis. Chapter 8 discusses the results and limitations of this research and provides recommendations for further research.. Chapter 9 concludes the main findings of this research.

2
Literature Review

2.1. Literature Review

In this section, an overview of existing literature about how demand for inland waterway transport changes in response to low water levels, the effects of modal shift on port-hinterland connections and an overview of the existing models in the literature will be provided.

2.1.1. Changes in transport demand for inland waterway transport

Compared to other transport modalities, inland waterway transport is more sensitive to climate-related aspects (Hendrickx & Breemersch, 2012). Fluctuations in water levels affect the costs and reliability of waterborne transport (Hendrickx & Breemersch, 2012). The transport capacity of inland waterway transport is reduced when it faces low water levels. Shippers are forced to transship cargo to shallow draught vessels, road or rail transport, which impacts the ability to serve transport demand.

Although more costly than inland waterway transport, road transport sees a major increase in case of low water levels due to the flexible character of road transport (Bedoya-Maya et al., 2024). Rail transport can take some load, but is more limited by available capacity and slot availability, and terminal congestion (Gandhi et al., 2024). Rail transport slots usually need to be booked weeks in advance, which makes it difficult to react to sudden change in demand. Besides switching to road and rail transport, shallower draft vessels can also be used, but are less efficient because of the smaller capacity and lower propulsion efficiency. This causes delays in container shipments.

Most research in the field of modal shift has been done on a shift from road to rail or inland waterway transport so the knowledge on modal shift from waterborne transport to road or rail remains limited. However, research has shown that about 5.4% of the annual European inland freight transport can be lost due to low water levels (Jonkeren et al., 2007). This study did not differ in types of cargo and vessels. Another study by Jonkeren et al. (2008) focused on barge transport and found that in the European inland waterway transport market, 3.2 million tons annually (which equals 5.2%) would be lost in the most extreme climate scenario. Bedoya-Maya et al. (2024) focused on inland container transport in low water periods and found that the impact of low water levels on container transport is a reduction of 0.2% per day of disruption and -5.9% when the disruption remained longer than 24 days. By 2050, between 7% and 20% of the annual container throughput can be lost if the drought resilience is not improved (Bedoya-Maya et al., 2024).

2.1.2. Modal shift and resilience of port-hinterland connections

The full potential of inland waterway transport in Europe remains underutilized (Bedoya-Maya et al., 2025). In response, some studies have examined strategies to enhance the drought resilience of port-hinterland connections, particularly during periods of low water levels. In one of these studies it was highlighted that an efficient fleet composition can significantly improve both the capacity and resilience of the inland waterway network (Hekkenberg, 2015). However, transitioning to a more effective fleet also requires adequate transshipment facilities to enable the unloading of cargo from the vessels. Gobert and Rudolf (2023) emphasize that enhancing the facilitation of intermodal transportation along the river is crucial for increasing the network resilience during drought conditions. Terminals contribute most effectively to the drought resilience when strategically located near river bottlenecks.

In addition to resilience benefits, a modal shift from road to waterway transport offers broader advantages. Calderón-Rivera et al. (2024b) demonstrate that such a shift can reduce costs associated with road congestion, climate change, and infrastructure wear. Furthermore, Jiang et al. (2024) show that shifting freight transport from road to inland waterways can lead to significant reductions in CO_2 emissions.

For the Rhine river, studies have identified bottlenecks near Nijmegen, Duisburg, and Kaub and identified a list of potential hub locations (Bedoya-Maya et al., 2025; Van der Plas, 2024). Nonetheless, there remains a lack of comprehensive knowledge regarding the optimal placement and specific functions of hubs needed to enhance the river's drought resilience. Consequently, the impacts of hub establishment on the overall transport system and on existing terminals are still not fully understood.

2.1.3. Application of hub establishment to improve drought resilience

Despite its potential, there is limited literature available on how low water levels affect the transport performance of waterborne transport and how the establishment of hubs impacts the transport system and contributes to enhancing drought resilience.

Racunica and Wynter (2005) focused on increasing the share of rail in intermodal freight transport by locating hubs without limiting the capacity of the hubs. This research shows, for rail, that optimal located intermodal hubs can significantly increase the utilization of the rail network. The intermodal hubs are found to contribute to both cost efficiency, reducing congestion and environmental impact. Arnold et al. (2004) also focused on locating rail/road terminals for freight transport.

Binsfeld et al. (2024) developed a model that uses EcoTransit methodology to minimize both the total transport costs and greenhouse-gas emissions by selecting modes, quantities, routes, and transshipments. It focuses on multimodal transport by inland waterway and truck under disruptions like infrastructure failure. They highlighted that optimization of hub location is crucial for balancing costs, emissions and resilience in case of disrupted canal operations. This research showed that, in case of infrastructure failure, the total costs can be reduced up to 28% by strategic location of hubs.

Nur et al. (2020) created a model to study the impact of fluctuating water levels on inland waterway management decisions in the United States. They found that, for their test region, up to 81.5% more barges are needed for the transport as a result of fluctuating water levels. This model is one of the few available that includes constraints on the effective loading as a result of the vessel draught and includes terminal capacity constraints.

Fazayeli et al. (2018) and Alumur et al. (2012) developed more generic models for a location routing problem in a multimodal transport network. Fazayeli et al. (2018) used the model to incorporate sea transport, road and rail transport. Alumur et al. (2012) used the model for transport by airplanes and trucks.

Bhurtyal et al. (2024) used two-stage stochastic optimization to model the impact of demand uncertainty on strategic infrastructure planning and decisions on transportation. The model aims to minimize the expected total costs and allows for extension of existing terminals with different sizes.

When modeling transport by vessels, the vessel loading cannot exceed the effective capacity. If the effective capacity is exceeded, there is a risk of grounding. Binsfeld et al. (2024), Fazayeli et al. (2018), and Bedoya-Maya et al. (2025) include constraints on vehicle capacity. However, the vehicle capacity of vessels is not often linked to the available draught. Schoeneich et al. (2023) identified fairway depth as an important factor affecting the competitiveness of inland waterway transport because it directly affects the effective loading of a vessel. Bąk and Zalewski (2021) contributed by demonstrating that the vessel loading significantly affects the cost-effectiveness of inland waterway transport.

Research focusing on multimodal routing while considering the available river draught and hub location for increasing the transport performance on the river remains limited. However, there are other studies using mathematical modeling focusing on multimodal transportation for different purposes. Ahadi et al. (2018) focused on a stochastic problem for budgeting dredging maintenance to maximize the total flow. Sun and Lang (2015) focused on reduction of carbon emissions of transport and waiting times. Hosseini and Barker (2016) focused on increasing the resilience capacity of an inland port in disruptions, among others, of telecommunications and water supply. Zhu et al. (2021) used mathematical modeling of multimodal routing for optimizing transport routes of tugs considering transshipments while minimizing the carbon emissions and waiting times. Aghalari et al. (2021), Li and Zhang (2020) and Marufuzzaman and Eksioglu (2016) studied specific cases in different countries and commodities to analyze the feasibility of integrating inland waterway transport in the multimodal transportation network.

The study by Van der Plas (2024) focused on inland waterway transport along the Rhine-Alpine corridor. The study developed a model to identify suitable locations along the Rhine River for transport hubs to overcome bottlenecks in the river. The performance of the potential locations of the transportation hubs was assessed using Multi-Criteria Decision Making. Due to limitations of the model on satisfying terminal capacity, the potential locations will be used as input for this research to determine which hub locations contribute to total cost minimization while considering terminal capacity.

In summary, the existing literature highlights several developments in multimodal transport optimization, hub location selection, and the integration of drought restrictions on the loading of vessels. However, few studies explicitly include the impact of low water levels on the effective vessel capacity or the role of hub establishment including the hub capacity in enhancing drought resilience. Furthermore, terminal capacity is often overlooked in hub location models. This leaves a gap in integrating water level-dependent vessel capacities, terminal capacity constraints, and the possibility of establishing new hubs and expanding existing terminals. Table 2.1 outlines the existing body of work on multimodal routing in transportation networks and serves as a comparative framework for analyzing the key characteristics of prior studies.

Table 2.1: General overview of the existing literature on multi-modal routing and hub establishment in port-hinterland transportation systems.

Reference	Available draught	Terminal capacity	Hub establishment	Transport modes			Solution Approach*
				Waterways	Road	Rail	
Arnold et al. (2004)			✓		✓	✓	ILP
Racunica and Wynter (2005)			✓		✓	✓	MINLP
Alumur et al. (2012)					✓		MILP
Caris et al. (2012)							
Sun and Lang (2015)		✓			✓	✓	MINLP
Marufuzzaman and Eksioglu (2016)		✓	✓	✓	✓	✓	MILP
Li and Zhang (2020)		✓			✓	✓	MILP
Fazayeli et al. (2018)			✓	✓	✓	✓	MINLP
Ahadi et al. (2018)	✓	✓		✓			MILP
Nur et al. (2020)	✓	✓		✓	✓		MILP
Aghalari et al. (2021)	✓	✓		✓			MILP
Bąk and Zalewski (2021)	✓			✓			PM
Zhu et al. (2021)							
Bhurtyal et al. (2024)		✓	✓	✓	✓	✓	2-SOP
Binsfeld et al. (2024)		✓		✓	✓		BMIP
Van der Plas (2024)			✓	✓	✓	✓	MCDA
Bedoya-Maya et al. (2025)	✓			✓			DES
This study	✓	✓	✓	✓	✓	✓	MILP

* ILP: Integer Linear Programming; MINLP: Mixed Integer Nonlinear Programming ;
MILP: Mixed Integer Linear Programming; PM: Polish Method of water channel design;
2-SOP: two-stage stochastic optimization; BMIP: Biobjective Mixed Integer Programming;
MCDA: Multi-Criteria Decision Analysis; DES: Discrete Event Simulation

2.2. Conclusion

From the literature review it can be concluded that low water levels significantly constrain the transport capacity of inland waterways resulting in a shift towards other transport modalities. This decreases the market share of inland waterways while there is potential to increase this market share.

Despite growing recognition of drought-related challenges, most existing research on modal shift focuses on transitions from road to more sustainable modes, leaving the shift from inland waterways to road or rail less understood. Nevertheless, studies estimated that 5–20% of inland freight transport could be lost annually under decreasing water levels without resilience improvements.

Strategically located hubs near river bottlenecks can play an important role in maintaining network performance during droughts. Yet, a gap remains in understanding where and to what extend these hubs should be established or existing terminals should be expanded to effectively increase drought resilience of the transport system along critical waterways such as the Rhine.

The general overview, presented in Table 2.1, indicates that the exploration of hub establishment in response to low water levels has received limited attention in the literature. This reveals a research gap that this study aims to address. While several studies have proposed variations of integer linear programming models for multimodal routing, few have centered waterborne transport as the primary mode, particularly in the context of modal shifts during low water conditions. This research aims to address the gap in the existing literature by presenting an approach to select hubs to be established and analyze the impact on the system by different transportation decisions as a result of these hubs.

As shown in Table 2.1, previous studies have often focused on only two transport modes, with waterborne transport sometimes entirely excluded. By integrating all three primary transport modalities this study addresses a critical gap and contributes to a more comprehensive understanding of multimodal resilience under drought conditions. In addition, this research allows for both the establishment of new hubs and the expansion of existing terminals, enabling analysis of their respective impacts on network performance.

3 Methodology Overview

Although the exact details of the methodology will be described more in depth in the next chapters, this chapter will give an overview of the methodology used in this research.

This research is based on three methods: data-analysis, mathematical modeling and scenario-based analysis. This research uses multiple datasets which required some pre-processing first. *Informatie- en Volgsysteem voor de Scheepvaart (IVS)* is a historical dataset that contains all vessels that passed Lobith between 1 January 2010 and 31 December 2024. This data did not include RWS types (a vessel profile as defined by Rijkswaterstaat to categorize vessels). Therefore, as part of preprocessing the data, the vessels have been labeled with the RWS type (of the types used in this research) that matches best the relation between the loading factor and the vessel draught. The data consists of 228 unique German destinations. To reduce the number of unique destinations, the destinations are clustered to the rail yard of the Deutsche Bahn that is located closest to the actual destination. More in-depth information on pre-processing of the IVS data will be provided in Chapter 4.

A historical dataset of river discharge measured at Lobith between 1 January 2010 and 31 December 2024 has been used in combination with a dataset of water levels measured at Lobith between 1 January 2024 and 31 December 2024 to link the river discharge to corresponding water level at Lobith. To compute the relation of river discharge and the water level for other sections in the river, the water levels were derived from Elwis (n.d.). Because information on the gauge stations where water levels were measured was missing, a relation between the water level at the gauge stations and the water discharge at Lobith had to be computed. From this information, the available draught was computed for different sections in the river. The available draught in different sections of the river is input for the mathematical model as it determines the effective loading capacity of the different vessel types. More in-depth information about how the available draught is computed will be provided in Section 5.3.2.

The data-analysis focuses on the impact of the river discharge measured at Lobith on the transported cargo passing Lobith and provides useful input for the mathematical model. It shows the relation between the loading factor and the vessel draught, and shows how this is used to label the vessels in the IVS dataset to the RWS types included in this research. After labeling the vessels with RWS types, the data analysis focuses on the share of each RWS vessel type on each day included in the IVS dataset. In addition, the data analysis focuses on changes in the loading factor of the vessels of each RWS type as a result of fluctuations in river discharges ranging from the normal river discharge of 1400 m^3/s and below. River discharge above 1400 m^3/s is not investigated, because above normal river discharge, the loading factor does not vary much compared to the normal river discharge level. From this analysis, it can be seen how the river discharge affects the usage of certain vessels. This will be used to determine the shipments which are input for the mathematical model. More in-depth explanation on the data analysis will follow in Chapter 4. How the data analysis can be used for certain input of the model will be further described in Chapter 5.

The list of potential hubs from Van der Plas (2024) was used as input for the mathematical model after some modifications. If potential locations that were selected by Van der Plas (2024) are being used for different purposes or locations are not located near the Rhine river, they were removed. Some potential locations have been added to the list as well if for instance free space was available near the rail infrastructure. Terminals that have sufficient free space around it to construct at least one extra quay have been added for terminal extension. More information on the hub locations will be provided in section 5.2.2.

With all this input, a mathematical optimization model has been developed to ship multiple shipments through the network towards the final destinations while minimizing the total cost for transporting all shipments. Mathematical modeling is used because of its capabilities of understanding complex systems and making optimal decisions given a set of constraints. The model includes existing terminals with direct connections to the Port of Rotterdam, potential new hubs and extended terminals that can be accessed only if they are selected for establishment or extension. Besides flow conservation and terminal capacity constraints, the model includes constraints on the vessel loading in order to not exceed the available draught of a certain section because that would increase the risk of grounding. The network and model were implemented in Python and a Gurobi solver was used for solving the optimization model. For the base model, the mathematical model was ran to simulate routing of the cargo when the river discharge at Lobith is normal (1400 m^3/s). From this base model, some key performance indicators were extracted: the total cost, the CO_2-equivalent emissions of the transport and the terminal utilization of terminals that are being used for transshipment. This base model is also used for a sensitivity analysis of the parameters affecting the total cost. More details about the model will be provided in Chapter 5 and Chapter 6 will provide and analyze the results of the base model.

The mathematical model will be used to analyze the transport performance in different scenarios. Scenario-based analysis is used to analyze the effects of lowering river discharge levels without changing the system, the effects of hub establishment when river discharge levels decrease and the effects of changing rail capacities in a certain river discharge level. The scenarios will be based on lowering river discharge levels and available capacity of the rail infrastructure. The available rail capacity is derived from the total cargo being transshipped to rail transport in the base model. In the scenarios, water levels decrease based on expected Agreed Low River discharges for 2050 and 2100 as defined by Van der Mark (2022). For the fluctuations in rail capacity, the rail capacity can decrease because of the political environment which can result in stronger preference for passenger transport by rail. The capacity of the rail transport network can also increase as a result of investments in the rail infrastructure. For the scenario-based analysis, the design of the network has to be defined first because it is not possible to select different hubs for different scenarios. In each scenario, a case will be simulated based on the existing terminals only and a case based on the new design of the network. From each scenario and each case, the same KPIs (total cost, CO_2-equivalent emissions and the utilization of terminals) have been extracted. The results of decreasing river discharge without establishing hubs and changing rail capacity will be compared against each other for the impact of decreasing water levels. In all scenarios, the results when hubs are established are compared to when no hubs are established to analyze the impact of hub establishment. Lastly, keeping a river discharge level constant (for the expected low river discharge of 2050), the impact of increasing the rail infrastructure will be analyzed. All these comparisons contribute to finding answers on the main research question.

Figure 3.1 gives an overview of the above described methodologies, how they are related to each other and what is exactly part of this research.

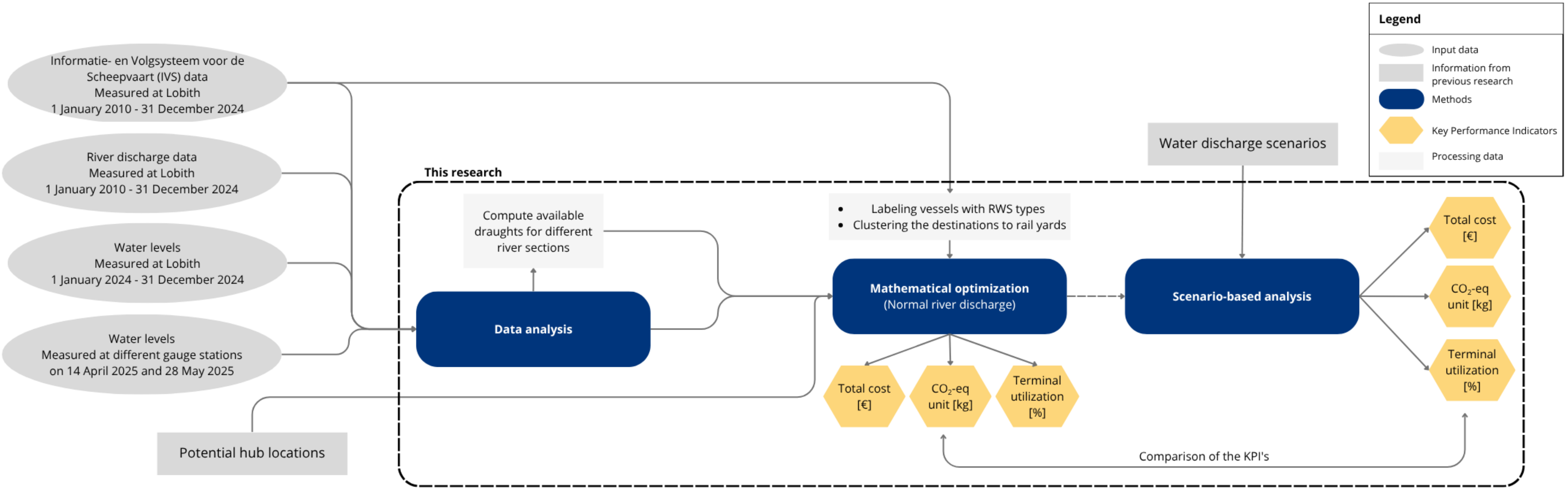


Figure 3.1: Visualization of the methodology used in this research.

4 Data Analysis

In this chapter, the datasets that were used in this research will be described. For each dataset, the preprocessing will be described and results of data analysis will be presented.

4.1. Data on water discharge at Lobith

One of the datasets used in this research is an open source dataset provided by Rijkswaterstaat. This dataset consists of river discharge data measured at Lobith in the period between January 1st, 2010 until December 31st, 2024 (Rijkswaterstaat, n.d.).

4.1.1. Data preprocessing

The data before January 1st, 2022 consisted of measured values only, whereas the data from January 1st, 2022 onward also consisted of the predicted values. The initial data did not consist of any missing values. However, the data did consist of some infinity values for water discharge. If the measured value for water discharge was reported as infinity before 2022, it had to be removed. In total, 1.17% of the data had to be removed. The infinite values from 2022 onward were replaced with the estimated value. Then all rows with estimated values had to be removed as well. Figure 4.1 shows the daily discharge levels measured at Lobith from 2010 until 2024. It can be seen that there are some periods where the water discharge level was below the current Agreed Low River discharge of 1020 m^3/s, indicating drought periods. The drought period at the end of 2018 had the longest duration in this period.

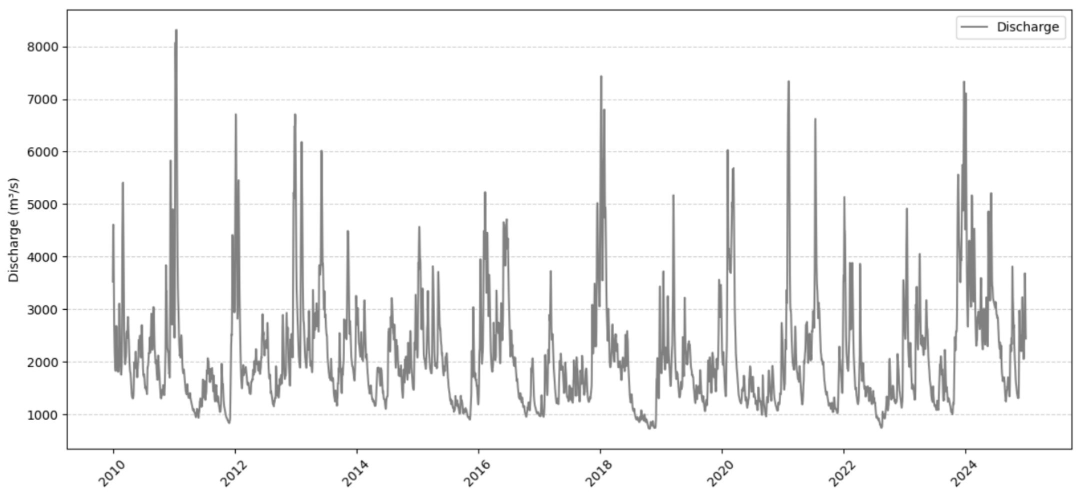


Figure 4.1: Historical discharge levels from January 1st, 2010 until December 31st, 2024 measured at Lobith.

Figure 4.2 shows the number of days per year with a river discharge below 1020 $^3/s$ measured at Lobith between 2010 and 2024. It can be seen that 2018 contained the most days with a river discharge at Lobith below 1020 m^3/s followed by 2022 and 2011. There are also years with 0 days where the river discharge is below the Agreed Low River discharge level.

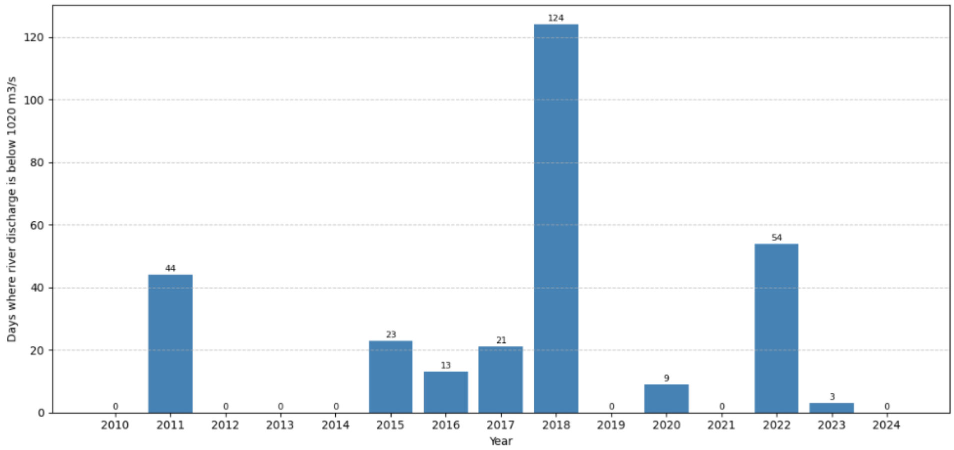


Figure 4.2: Number of days per year with a river discharge at Lobith below 1020 m^3/s.

4.1.2. Water levels

To compute the effective loading capacity of vessels later on, the maximum available draught has to be computed for different sections of the river. Therefore, the water discharge levels have been linked to the actual water levels at Lobith between 1 July 2024 and 1 January 2025. For this, outliers had to be removed after which interpolation filled in the missing values. The results of this comparison are plotted in Figure 4.3. The discharge levels and water levels are correlated with a coefficient of 0.995. The Agreed Low River discharge level of 1020 m^3/s results in a water level of 739 cm at Lobith (Ministerie van Infrastructuur en Waterstaat, 2024; Vinke et al., 2024).

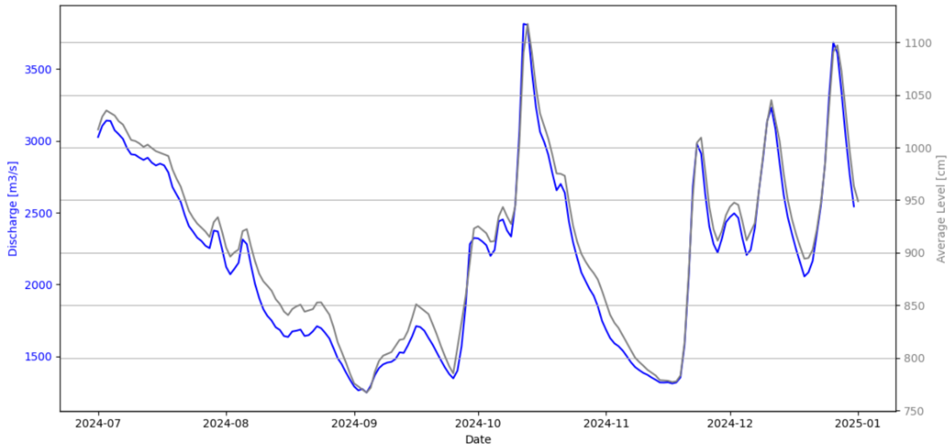


Figure 4.3: Discharge levels and water levels at Lobith between 1 July 2024 and 1 January 2025.

The water discharge Q is not linear related to the water level. Based on the water level, the river discharge can be computed with Equation 4.1.

$$Q = a(h - h_0)^b \tag{4.1}$$

Equation 4.1 can be used to compute the discharge at a certain location in cubic meters per second. In this equation, h_0 is the theoretical level where the water flow stops, also called the base level. h is the water level or stage in meters. a and b are respectively the scaling factor and an exponent to control the effect of discharge on the water level.

To compute the water level in Lobith based on th water discharge, Equation 4.1 can be reformulated to:

$$h = h_0 + (\frac{Q}{a})^{\frac{1}{b}} \tag{4.2}$$

The Rhine river has different depths of the fairway at Agreed Low River discharge depending of the section of the Rhine river, which can be seen in Appendix C. Besides that, the flow is not equal over the whole river. Therefore, for each river section, the values of a and b would have to be estimated again. This is not possible due to lacking open data of river discharge and the corresponding water levels measured at different locations in the Rhine river. Therefore, a linearization of the relation between the river discharge and water level at Lobith has been analyzed. As the model will only focus on a river discharge of 1400 m^3/s and below, the larger river discharge levels have been excluded from this linearization. Figure 4.4 shows the results of this linearization. The R^2 value is 0.872 meaning that the variance of the relation between the river discharge and the water level at Lobith can be explained for 87.2% by a linear relation.

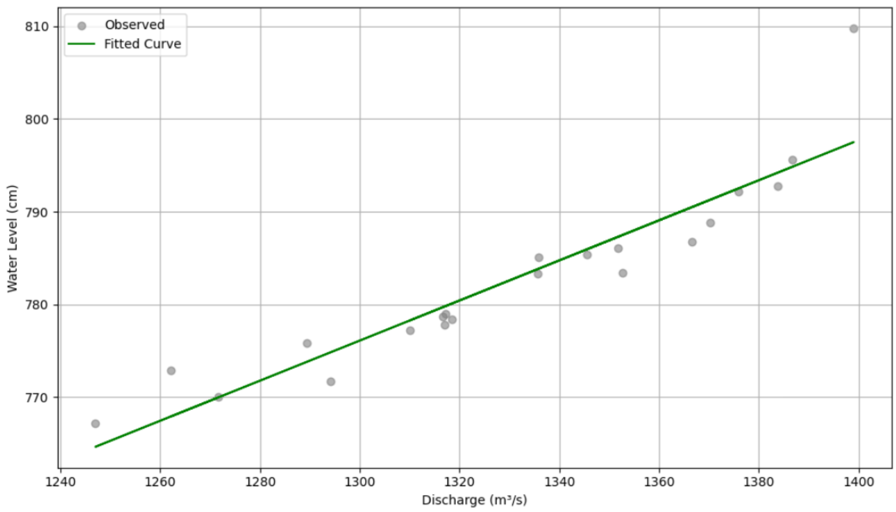


Figure 4.4: Linearization of the relation between river discharge and the water level at Lobith for river discharge levels below 1400 m^3/s.

Details on the linearization of the relation between the actual water level and the river discharge at Lobith can be found in Appendix C.

4.2. IVS data

In this research, IVS data has been used. IVS is short for *(in Dutch:) Informatie- en Volgsysteem voor de Scheepvaart*, which can be translated to Shipping Information and Tracking System. The IVS data has been provided by Rijkswaterstaat. This dataset consists of vessels passing Lobith between January 1st, 2014 until March 9th, 2025. Table 4.1 shows the information that included in the columns of the dataset. Each row in the dataset represents a vessel passing Lobith within the specified time period.

Table 4.1: Explanation of the used variables of the data.

Variable name	Meaning
Jaar	Year
Maand	Month
Dag	Day
v05_06_begindt_evenement	Moment of measurement
v38_Vervoerd_gewicht	Transported weight
v18_Laadvermogen	Loading capacity
v40_1_Herkomst_land	Country of origin
v40_2_Herkomst_plaats	Place of origin
v41_1_Bestemming_land	Country of destination
v41_2_Bestemming_plaats	Place of destination
v22_Scheepslengte	Length of the vessel
v23_Scheepsbreedte	Beam of the vessel
v24_Diepgang	Draught of the vessel
NST_2007	Type of cargo based on Centraal Bureau voor de Statistiek (n.d.-a)

The origin and destination of the vessel are specified in country and place, where the country is abbreviated in two characters and the place is abbreviated in three characters. The abbreviations are derived from the Code for Trade and Transport Locations as defined by the United Nations.

4.2.1. Data preprocessing

To preprocess the data, it had to be sorted by date first and duplicate rows were removed. The minimum and maximum values of the transported weight, loading capacity, length, beam, and draught indicated the necessity of rescaling and removing values. Vessels with a length over 200 meters, a width over 25 meters or a depth over 5 meters were removed as well as zero values. In some cases, the loading capacity had to be rescaled. The transported weight cannot exceed the vehicle capacity with more than 10%. This threshold has been chosen so that not too much data has to be rescaled or removed. The remaining data (8%, which equals 1.1 million datapoints) was used to compute the daily transported weight which can be compared to the daily discharge levels in Figure 4.5. The Agreed Low River discharge level of 1020 m^3/s is also shown. (Vinke et al., 2024).

In Figure 4.5 it can clearly be seen that from the drought period in 2018, part of the cargo is shifted away from inland waterway transport. Ever since, the transported weight of all cargo types on vessels passing Lobith has not returned to the same amount as before the drought period in 2018.

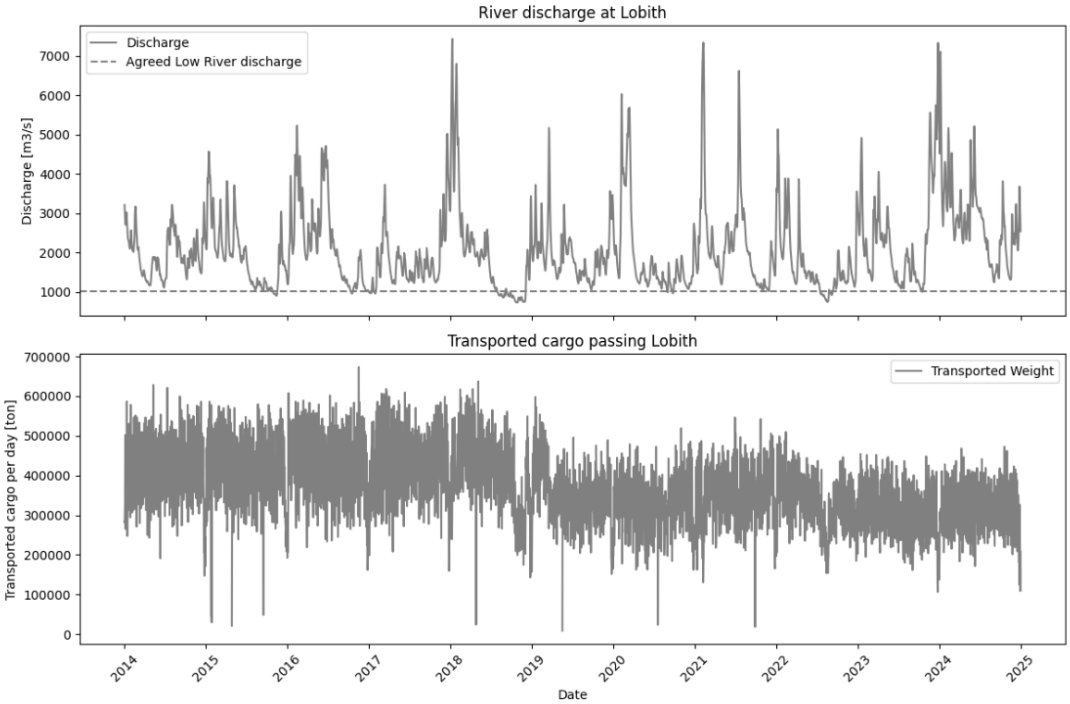


Figure 4.5: The daily discharge and the transported weight of all cargo types at Lobith from 2014 to 2024.

The transported weight in Figure 4.5 includes all categories of cargo that were included in the data. Based on the Commodity Nomenclature, the categories 4, 5, 6, 8, 11, 13, and 16 are considered to be transported generally by standard containers (Centraal Bureau voor de Statistiek, n.d.-a).

In total, this dataset consists of 2919 unique origins and destinations in 112 countries. Focusing on transport from Rotterdam to the hinterland reduces the number of unique origins and destinations to 720 locations in 38 countries. Narrowing down the focus to container transport from Rotterdam to Germany reduces the number of unique locations to 228. Reduction of the number of final destinations is necessary to reduce the complexity of the network that will be investigated in this research. Therefore, the final destinations will be labeled with the closest located rail yard of the Deutsche Bahn. This will be explained more in Chapter 5.

For most of the vessels, the loading weight is known. After removing the missing values and double measurements, the data consists of some errors. For some vessels, the loading weight is a factor 10 or 1000 too high. This can be the result the unit in which the weight has been measured. The values that are a factor 10 or 1000 too high have been rescaled by simply dividing the weight by the factor. There are cases where the weight is larger than the loading capacity. To correct for these incorrect measurements, a 1.1 threshold for the loading factor has been used to select which values had to be removed in order not to remove too many data points. The loading factor (LF) is computed as follows:

$$\text{LF} = \frac{\text{Transported weight}}{\text{Transport capacity of the vehicle}} = \frac{\text{V38\_Vervoerd\_gewicht}}{\text{v18\_Laadvermogen}} \tag{4.3}$$

The loading capacity of inland vessels is constrained by the available water depth of free-flowing rivers (Dorsser et al., 2020). Inland vessels require a minimum water depth to sail which depends on the draught required to keep the propellor sufficiently submerged and the minimum under keel clearance to avoid grounding (Dorsser et al., 2020). Rhine vessels have a linear relation between the loading factor and the vessel draught (Dorsser et al., 2020).
The effective capacity of a vessel is affected by the available draught. Individual ship owners know how to load their vessel to reduce the draught of the ship to adapt to low water levels (Dorsser et al., 2020). However, knowledge remains limited on how low water levels affect the overall transport capacity of the network (Dorsser et al., 2020). High water levels allow for higher loading factors because of increased

effective capacities compared to the effective capacities in low water scenarios. In case of normal water levels, the vessel can have a larger draught than in case of low water levels. Vessels with the largest loaded draughts are most vulnerable to reduced river discharge levels (Vinke et al., 2024; Anku et al., 2024.

Although the length, beam and draught are known for the vessels in the IVS data, they vessels are not labeled with a CEMT or RWS class. To get more information about the vessels in the IVS dataset, the vessels in the data have been labled with the RWS type where the vessel draught has the smallest error with the vessel draught as computed by the linear relation of vessel draught and loading factor for each RWS type. The labels are derived from the research by Vinke et al. (2024). Figure 4.6 shows the relation between the loading factor and vessel draught of the vessel types included in this research. It shows that M2 and M6 have the same draught when the loading factor is 0.57. It is important to note that both vessels have different transport capacities, meaning that the loading in weight is different but the loading factor is similar. Figure 4.6 also shows an intersection between M4 and M6 vessels at a loading factor of 0.71.

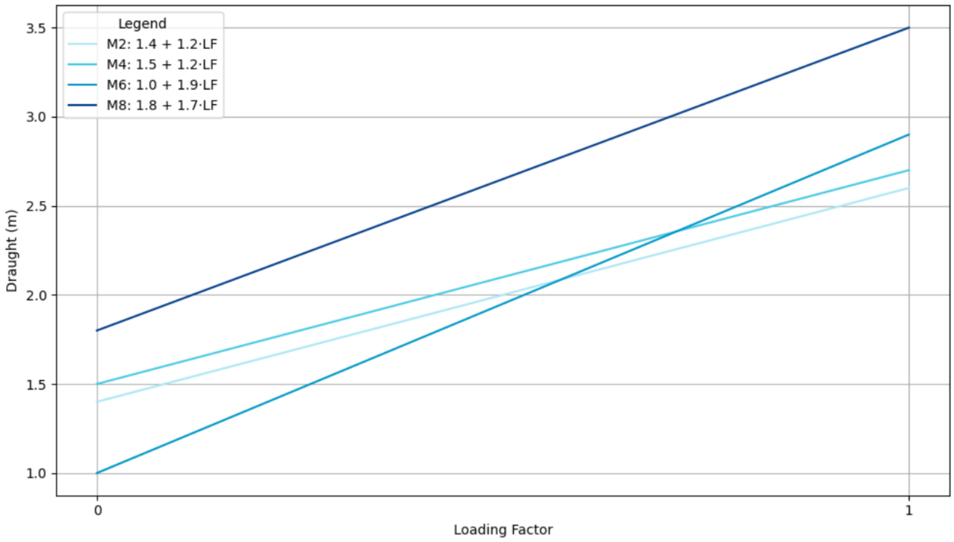


Figure 4.6: Relation between the loading factor and the vessel draught of M2, M4, M6, and M8 type vessels.

Based on the relation between the empty and loaded draught of the different vessel types and the corresponding loading factors, the vessels in the IVS data have been clustered to the RWS lables *M2, M4, M6* and *M8*. The results of the labeling are shown in Figure 4.7. Because of the intersections in the linear relations of vessel draught and loading factor, the plot of labeling the vessels turned out to be as presented in the Figure. For each vessel, the draught and the loading factor are known which are used for the labeling.

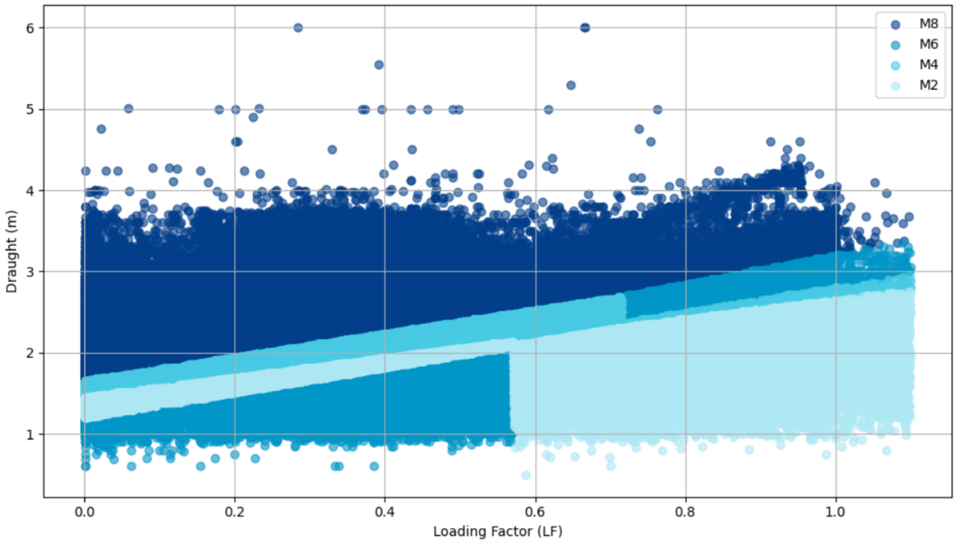


Figure 4.7: Vessel data clustered to RWS categories based on the length, beam and draught of the vessels

Each day, different numbers of vessels of each type sailed passed Lobith. Figure 4.8 shows for each day the share of a specific vessel type compared to all vessels passing Lobith on that day. The share of a vessel type on a day can be computed by:

$$\text{Share of vessel type i on day x} = \frac{\text{Number of vessels of type i}}{\text{Total number of vessels on day x}} \tag{4.4}$$

In Figure 4.8 it can be seen that in case of low water discharge levels, the share of M8 vessels (which are large Rhine vessels) decreases strongly. Although transported cargo also drops, it can be seen from Figure 4.5 that the transported cargo is never zero. Instead, smaller vessels are used more often and loading factors of the used vessels decrease.

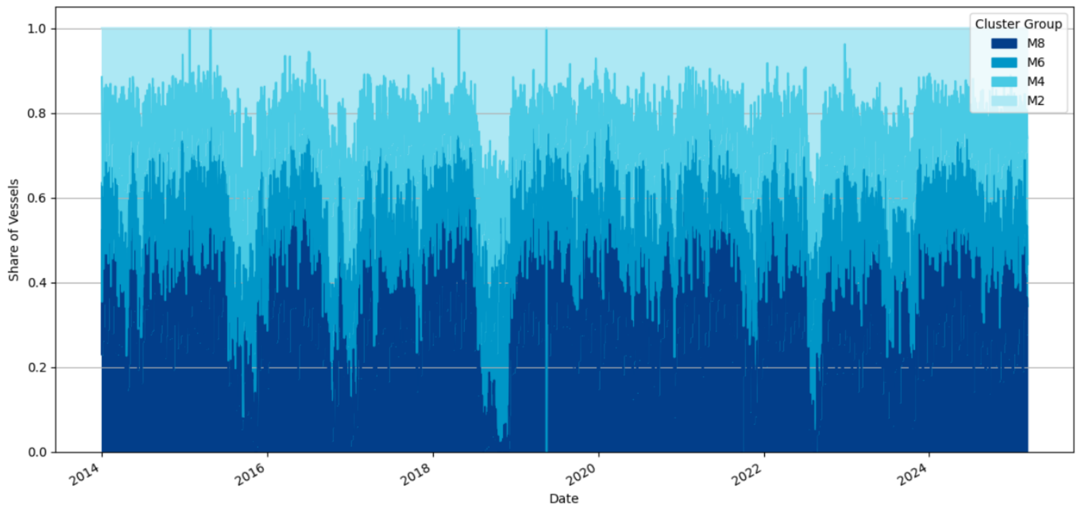
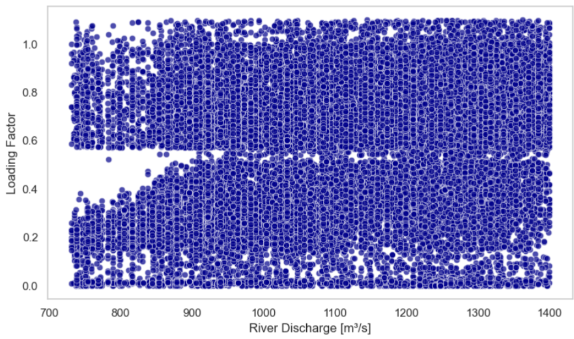


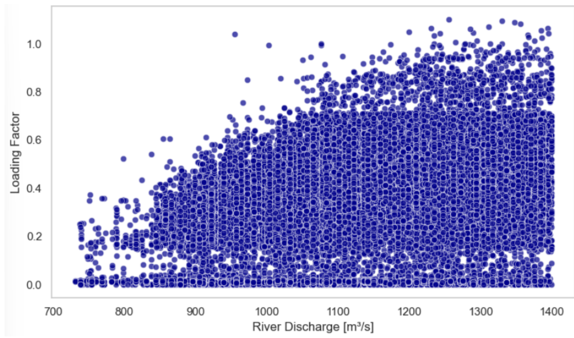
Figure 4.8: Daily share of each vessel type (RWS-class). Colors are similar to the clusters in Figure 4.7.

Dropping water levels change the share of a certain vessel type of all vessels passing Lobith per day but also affect the loading factor of the vessels. Figure 4.9 shows the loading factor for each RWS type from 1400 m^3/s and below. The limit of the x-axis is defined up to 1400 m^3/s, because with higher river discharge levels, the loading factor was found to remain about equal. Zooming in on the river discharge levels below the normal level of 1400 m^3/s makes the change in loading factors better visible.

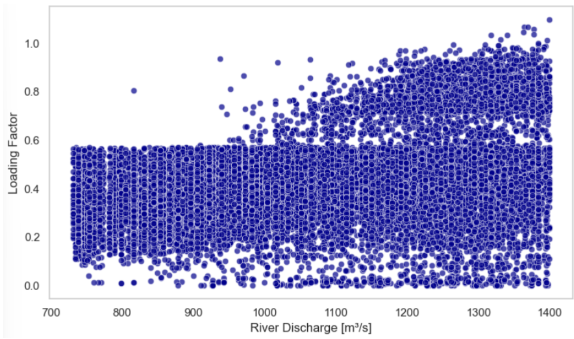
From these figures it can be seen that the loading factor of M2 vessels varies between 0 and 1 even when the river discharge levels drop below Agreed Low River discharge. A fully loaded M2 vessel would have a draught of 2.6 meters. Here it should be noted that the data is measured at Lobith, which as a relatively deep available draught compared to other sections in the Rhine river. Besides, in the data it is not specified in what exact terminal the cargo will be unloaded. In the plot of the M4 labeled vessels, it can be seen that the loading factor decreases from 0.8 at the Agreed Low River discharge level to 0.4 when the river discharge is 800 m^3/s. For M6 vessels it can be seen that when the river discharge drops to 950 m^3/s, the loading factor does not exceed 0.6 except for some outliers. For M8 vessels, it can be seen that the loading factor drops from 0.5 at Agreed Low River discharge to very low factors when the river discharge is 800 m^3/s. Some outliers can be seen in this plot as well. However, the number of outliers is strongly reduced by pre-processing of the data.



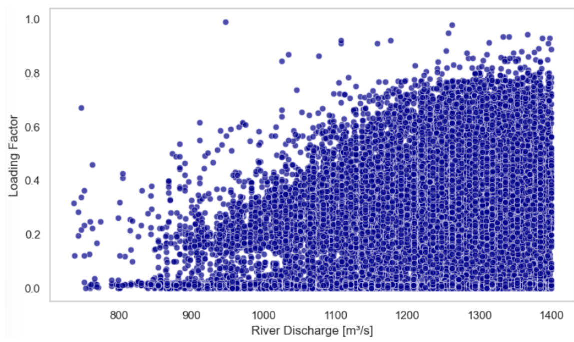
(a) Loading factors of M2 labeled vessels for each river discharge level.



(b) Loading factors of M4 labeled vessels for each river discharge level.



(c) Loading factors of M6 labeled vessels for each river discharge level.



(d) Loading factors of M8 labeled vessels for each river discharge level.

Figure 4.9: Loading factor vs river discharge (≤1400 m^3/s) for all M6 and M8 labeled vessels

From the data analysis, it can clearly be seen that when river discharge drops, the share of M8 vessels drops as well as the loading factors of these vessels. Table 4.2 shows the average number of vessels passing per day when the river discharge is around 1400 m^3/s and around 1020 m^3/s and the corresponding average loading of the vessels passing for each RWS-type included in this research. For the days that the river discharge is around 1400 m^m/s, all days where the river discharge is between 1390 and 1410 m^3/s are selected. For the days that the river discharge is around 1020 m^3/s, all days where the river discharge is between 1010 and 1030 m^3/s are selected. This was chosen, because the river discharge data contains only one measurement per day. Therefore, the number of days where the river discharge is rounded to the exact value are limited.

From Table 4.2 it can be seen how the number of vessels are affected when river discharge drops from 1400 m^m/s to 1020 m^3/s. It can be seen that when the river discharge is 1400 m^3/s, on average 89 container vessels pass Lobith. However, when river discharge is 1020 m^3/s, the average number of M2 and M6 vessels increase strongly, while the average number of M8 vessels decreases strongly. The number of M2 and M6 vessels increase which can be a result of a shift from M8 vessels to shallower draught vessels. It can also be seen that the number of M4 vessels slightly increases, but the average loading decreases with 26.4%. From the average loading per vessel type, it can also be seen that the average loading decreases with lowering water levels. These results show that using shipments of a day where the river discharge is 1400 m^3/s would overestimate the amount of cargo on a vessel to be routed through the network compared to when the river discharge drops to 1020 m^3/s. This information will be used later on to determine the input variables for the model.

Table 4.2: Average number of vessels passing Lobith per day where discharge is approximately a certain level and the average loading. The RWS labels as a result of the data preprocessing have been used for this.

Discharge at Lobith = 1400 m^3/s		
Vessel type	**Observations**	**Average loading**
M2	20	1609
M4	25	1276
M6	13	1473
M8	31	1064
Discharge at Lobith = 1020 m^3/s		
Vessel type	**Observations**	**Average loading**
M2	33	1421
M4	28	939
M6	21	1124
M8	13	577

5 Problem Description and Mathematical Model

5.1. Problem description

This research considers a multi-modal routing problem and a location problem for port-hinterland logistics. The network allows for transport by different types of inland vessels (M2, M4, M6 and M8 vessels), road and rail transport. All cargo has to be transported from the origin to the destinations. The destinations (in real-world rail yards of the Deutsche Bahn) all have different demand which is split into multiple shipments. The shipments are not of equal size as they are based on the IVS data. The cargo has to leave the origin (Rotterdam) by a waterway edge (because the IVS data contains vessels passing Lobith), which means that cargo can be transported by either a M2, M4, M6 or M8 vessel. The initial vessel is defined in the shipment and has been derived from the IVS data.

The Rhine river is simulated based on sequential connections between the terminals with direct connections to the Port of Rotterdam (Port of Rotterdam, 2024). The terminals facilitate modal shift from one modality to another or from one vessel to another, shallower draught vessel. Each vessel type is considered a unique modality. For instance, if a shift from M6 to M2 vessel occurs, this is considered as a modality shift. Each vessel has cargo of only one shipment with a destination which cannot be consolidated in this model.

Besides the existing terminals with direct connections, there is a subset of terminals which are potential new hubs. The potential hubs have the same functioning as the terminals but they do not exist yet. This means that cargo can only be routed through the hubs if the hub is established. Therefore, the hubs are not on the direct links between the terminals because these links do not allow for flow if the terminal is not selected. There is also a subset of terminals of which the size and the handling capacity can be extended. These are modeled the same as potential new hubs. The terminals that can be extended are modeled as new nodes (at the same location as the existing node) with an arc from the terminal downstream, an arc to the terminal upstream and rail and/or road arcs, similar to the original node, to the final destinations. The waterway arcs to the terminals that can be extended, must be used when the terminal is selected for extension. If a terminal is selected for extension, the original arcs cannot be used anymore.

All terminals (including the potential new hubs) have sequential waterway connections to other terminals (a link to the terminal downstream and a link to the terminal upstream of the terminal) and a direct link to destination nodes. These direct links to destinations always allow for road transport. Only if the terminal has access to rail infrastructure, there is also a link from the terminal to the final destinations that allows for rail transport. Once the cargo leaves the terminal by truck or train, it will directly be transported to the destination. Figure 5.1 shows a simplified overview of the graph that is used to model the problem.

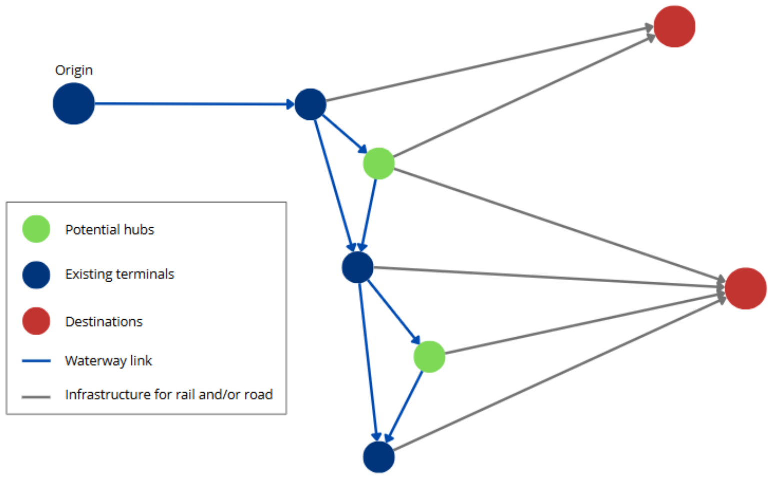


Figure 5.1: Graph of the problem.

5.1.1. Admissible edges

This research considers a multi-modal multi-echelon location and routing problem. The first echelon involves waterborne transport from Rotterdam to a terminal or hub located along the Rhine river where cargo is transshipped to road or rail transport. Terminals and hubs are transshipment locations where echelons meet. In terminals and hubs, vessels can be unloaded. The second echelon includes the flow of trucks and trains from the terminals and hubs to the final destination. In the terminals and hubs, cargo can also be reloaded to waterborne transport (shallower draught vessels M6, M4 and M2) which is still part of the first echelon.

The admissible edges differ per transport modality and per vessel type. All vessel types start from the origin and sail to a terminal or hub. In a terminal or hub, cargo can be unloaded. This cargo can be loaded to shallower draught vessels (M6, M4, M2) to sail further over the Rhine river to a terminal or hub more upstream. From there, or directly in the first terminal or hub of transshipment, the cargo can be reloaded to road or rail transport to head directly to the final destination. Cargo is not allowed to be transshipped to another M8 vessel in a terminal or hub other than Rotterdam. Cargo cannot reach the final destination by other transport modalities than road or rail. Lastly, cargo can only reach the final destination by rail if the terminal or hub in which the cargo was transshipped has access to rail infrastructure.

The problem is modeled on a directed graph $G(N,E)$ where N represents the set of nodes and E is the set of arcs. N includes the set of terminals T, including the subset of potential new hubs (H), and the subset of existing terminals that can be extended (P) and the set of origins (O) and destinations (D). $N = N_1 \cup N_2$ includes the set of nodes in the first echelon (N_1), and second echelon (N_2). The set $N_1 = O \cup T$ includes the origin (O) and the transshipment terminals. The set $N_2 = T \cup D$ includes the set of terminals, including the potential new hubs, the terminals that can be extended and the final destinations (D). $E = \{(i,j) | i,j \in N, i \neq j, (i,j) \in A \cup B \cup C\}$. A holds for M8 vessels departing from the origin to a transshipment terminal along the Rhine river. B holds for shallower draught vessels, not Large Rhine vessel (M2, M4, M6). C holds for transport by train and truck, where transport by train is only possible if node i has access to rail infrastructure.

$$A = \{(i,j) | i \in O, j \in T\}$$
$$B_1 = \{(i,j) | i \in O, j \in T\}, B_2 = \{(i,j) | i \in T, j \in T\}$$
$$C = \{(i,j) | i \in T, j \in D\}$$

The distances of all arcs are Euclidean distances. The nodes are therefore modeled on their coordinates. The waterway edges have a maximum draught that affects the effective loading capacity of the different vessel types on a link.

5.2. Model characterization

In this section the types of nodes will be described and the implemented network will be presented.

5.2.1. Container terminals

The Rhine river is modeled by sequential links between the terminals with direct access to the Port of Rotterdam (Port of Rotterdam, 2024). The terminals, terminal characteristics, and the corresponding coordinates can be found in Appendix A. For each terminal, it is known if the terminal has access to rail infrastructure to allow for cargo being shifted to rail transport. For each terminal, the number of cranes is also reported in Appendix A. The number of cranes in each terminal has been derived from either the fact page on the websites of the terminals, or by satellite pictures of Google Earth. The number of cranes will be used to determine the terminal capacity for loading and unloading vessels. For visualization reasons, the terminals are labeled with a code because the names are too long to write next to the node in the graph.

5.2.2. Hub locations

Research by Van der Plas (2024) has identified 3 bottlenecks on the Rhine river: Nijmegen, Duisburg and Kaub. The bottleneck at Kaub is known for the low available river draught. The bottleneck at Duisburg has been identified because of its industrial role in the Rhine-Ruhr area. The bottleneck of Nijmegen has been selected because of the critical point for water depth in the Netherlands (Van der Plas, 2024).

The bottlenecks in Nijmegen and Kaub compel vessels to carry less cargo to decrease vessel draught and pass navigable thresholds. The potential hubs are located downstream the bottlenecks so that they can facilitate modal shift in case of low river discharge. However, given the map of Rijkswaterstaat (n.d.), the water level at Druten (20 kilometers downstream Nijmegen) is lower compared to the water level at Nijmegen. Therefore, the potential new hub locations between Druten and Nijmegen are less beneficial in case of low river discharge. Although Duisburg is not a bottleneck because of the available draught, the terminals in the area are under a lot of pressure because of the central role in the industrial region. Therefore, this research also includes some potential hubs around Duisburg which can, in some scenarios, be selected if the terminal capacities are not sufficient for the cargo that has to shift modality in that region.

The potential hubs locations for the different bottlenecks used in this research are based on the lists developed by Van der Plas (2024). The list for each bottleneck has been modified a bit. Hubs that are not located near the river are removed, as well as potential hub locations where buildings with other purposes are build (e.g. a baseball stadium). Some potential hubs that were in the list of Nijmegen were also removed. Nijmegen has a river depth of <535 cm in case of low water (Rijkswaterstaat, n.d.). However, 20 kilometers downstream Nijmegen (near Druten), the river depth is <365 cm (Rijkswaterstaat, n.d.). Some of the potential hub locations in the list for Nijmegen are located downstream Druten, which is preferred to make the transport system more robust against climate change. Therefore, the potential hubs upstream Druten are also removed from the list of potential hubs for Nijmegen. The final set of potential hubs with the corresponding information can be found in Appendix B.

For each potential hub, the number of cranes that would be available after establishment, the size of the hub area, and if the hub has access to road and rail is known. The number of cranes will be used to determine the handling capacity of the hub. Similar to the existing container terminals, each hub has road connections from the hub to the final destinations. Only if the hub has access to rail infrastructure, the hub has also connections to the final destinations that allow for rail transport.

Figure 5.2 visualizes some potential hubs downstream near Druten. It shows the potential locations along the Rhine river and it shows for each potential hub location the connections to the road and railway network. Here it can be seen that the the potential rail terminal has connections to both road and railway, whereas the other potential hub locations are not connected to the railway network.

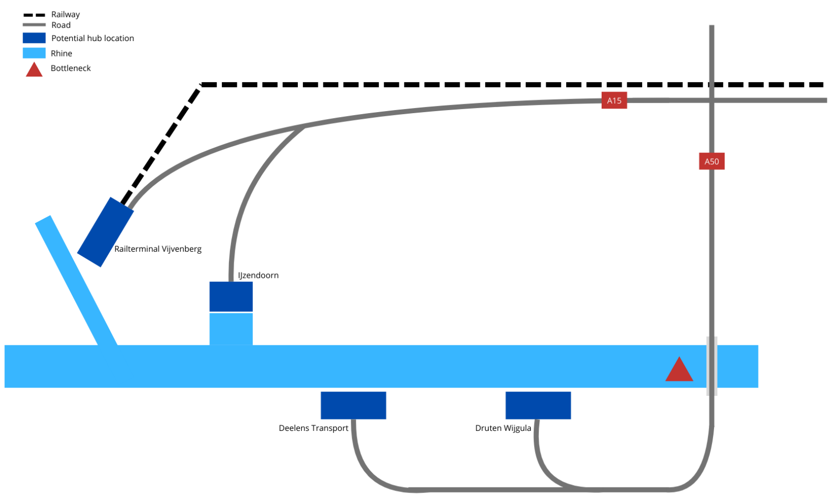
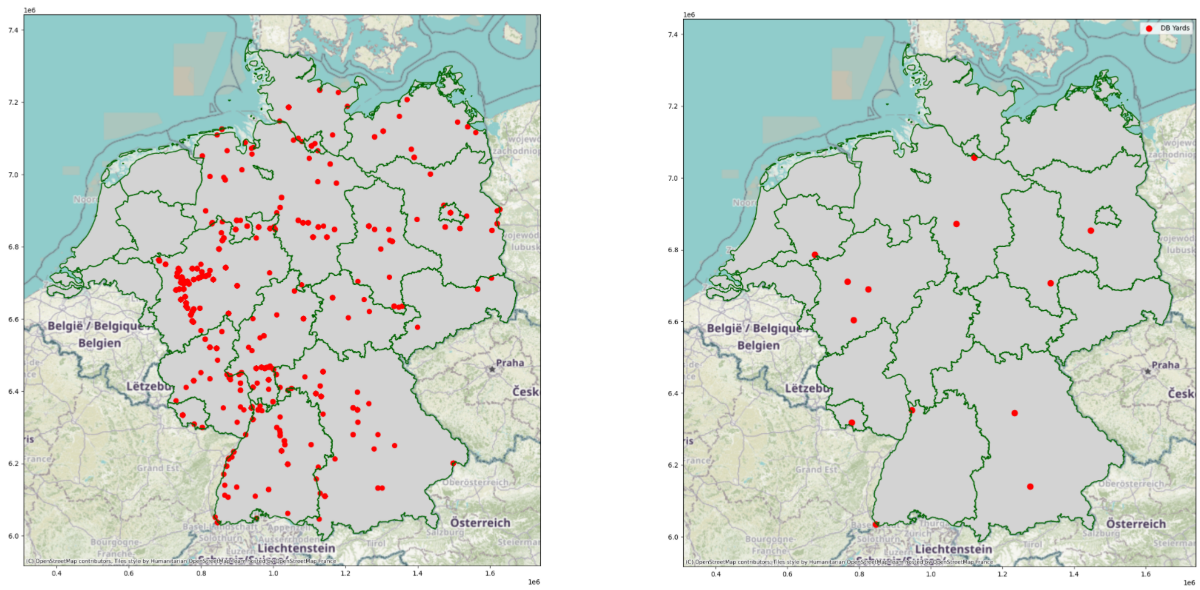


Figure 5.2: Visualization of connections to road and rail for potential hub locations downstream Nijmegen.

5.2.3. Destinations

In this research, transport from the Port of Rotterdam to the hinterland of Germany is investigated. Figure 5.3a shows all German destinations for container transport originating from Rotterdam in the IVS data between 1 January 2014 and 31 December 2020. Because of the large number of destinations in Germany, it was chosen to group the destinations to the closest rail yard of the Deutsche Bahn and Zevenaar. Figure 5.3b shows the rail yards included in this research which are used to label the final destinations in the dataset to. Therefore, Figure 5.4a show the results of labeling the destinations from the IVS data to the rail yards. Each yard has its own color and all terminals with the same color are in the cluster of the rail yard. The shipments, later on, will have the rail yard to which the original destination is closest by as their final destination.

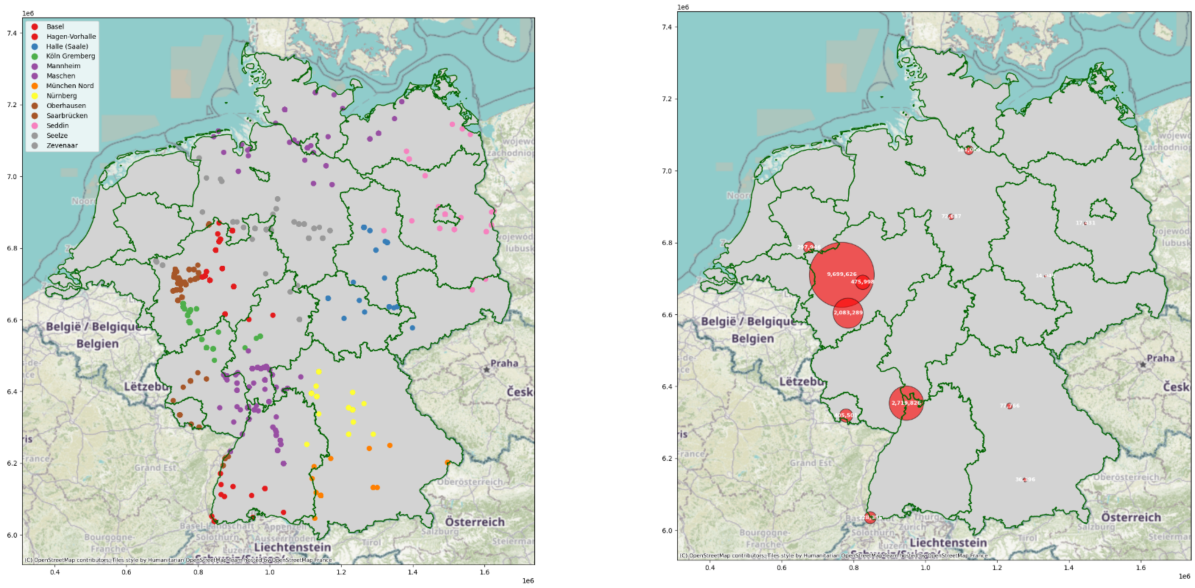


(a) All German destinations for container transport from Rotterdam to Germany.
-

(b) The rail yards included in this research. Including railyards of the Deutsche Bahn and Rotterdam and Zevenaar.

Figure 5.3: Overview of the destinations for container transport from Rotterdam to Germany in the IVS data from 1 January 2014 to 31 December 2020 and a representation of the transport networks by rail and waterway.

Figure 5.4b plots again the rail yards in the network. The size of the markers represents the average annual weight in tons that has to be transported to all destinations that are clustered to that rail yard. The bigger the marker, the more cargo needs to be transported to that rail yard. The markers are all scaled with the same scaler so the sizes can directly be compared against each other. From this figure it can be seen that, on a yearly basis, most cargo has to be transported to the yards in Oberhausen, Köln and Mannheim. Transport to east Germany is way less. Here, it should be noted that this figure is based on cargo measured on the Rhine near Lobith. It could be that the actual demand for destinations in East-Germany is larger but is transported by other modes of transport or via other ports, not passing Lobith.



(a) Destinations clustered by the closest rail yard.
-

(b) Comparison of average annual weight transported to each rail yard.

Figure 5.4: Overview of which destinations belong to which cluster and the average amount of cargo to be transported on annual basis to each yard.

Table 5.1 shows a part of the origin destination matrix of container transport from Rotterdam to the destinations as shown in the table. The demand data consists of the transported weight (tons) for each day to all destinations that are in the cluster (rail yard).

Table 5.1: Origin destination matrix (where the rail yards are the destinations) of container transport demand from Rotterdam to destination in tons.

Date	Köln	Mannheim	Oberhausen	...
2014-01-01	6560.0	7313.0	13095.5	...
2014-01-02	5609.0	13237.0	6200.0	...
...	...	...	...	...
Daily average	4061.0	8355.0	14956.0	...

5.2.4. Network representation

Figure 5.5 shows what the in Python implemented network looks like. For better visibility, the terminal names have been recoded to numbers, where 1 = Port of Rotterdam. The hub locations have also been recoded to numbers. The recoding can be seen in Appendices A and B. All terminals are sequentially connected (1 is connected to 2, 2 to 3, and so on). The hubs are connected to the first terminal upstream and the first terminal downstream the hub. All waterway connections allow for M2, M4, M6 and M8 vessels as long as their loading does not exceed the effective loading capacity. If the effective loading capacity is exceeded, there is a risk of grounding. All terminals and hubs have connections to the destinations, but the land infrastructure connections conditionally allow for rail transport.

As the IVS data is taken as a base for the shipments, all cargo has depart from the Port of Rotterdam by waterborne transport. The IVS data only consists of vessels passing Lobith and does not include shipments that depart from the Port of Rotterdam by road or rail transport. Therefore, the Port of Rotterdam (node 1 in the graph) only has a waterway connection to the first directly connected terminal.

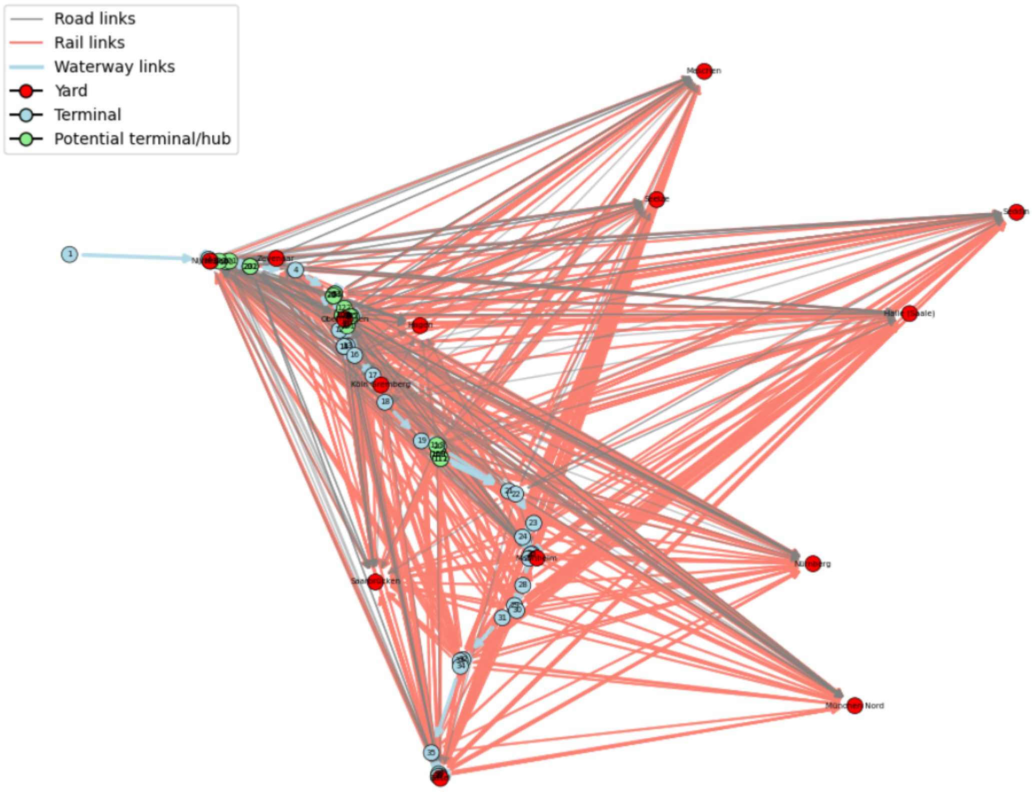


Figure 5.5: Implementation of the network.

5.3. Mathematical model

This section presents and explains the mathematical model. The model is based on the model of Huang et al. (2025), who modeled path optimization for multi-modal container transport from the hinterlands to the port of Shanghai. The main differences in the model described in this section, is that the cargo is labeled with a shipment and that for each shipment the destination is tracked and preserved. This model focuses on port-hinterland transport.

5.3.1. Assumptions and simplifications

O'Kelly and Miller (1994) compared many literature studies on hub location problems and found that the design problem quickly becomes very complex for all network topologies but the simplest. This forces researchers to make problem assumptions to approach the problem. The model routes the cargo of the shipments from the origin to the destinations by choosing a path to minimize the total costs. A path is the route from the origin to the destinations that minimizes cost. The routing and hub selection is subject to the following assumptions and simplifications:

1. All cargo of all shipments has to leave the origin and has to reach the destination of the shipment. Different shipments cannot be consolidated on the same vessel. Therefore, it is important to track the cargo flows in the vehicles for individual shipments. Trucks and trains can only originate from a terminal (or potential new hub if the hub is selected) and head directly towards the final destination of the cargo. This is covered in the network by direct arcs from the terminal to the final destination. Vehicle flows are tracked for the vessel, so it is known how much cargo of what shipment is unloaded of the vessel and shifted to another vessel of the same type or another modality, which can be a shallower draught vessel, train or truck.
2. For multi-modal container transportation, transport by road, rail, and inland waterway is considered. Waterway transport can be done by M2, M4, M6 or M8 Rhine vessels. Between 2014 and 2020, M8 and M6 Rhine vessels passed Lobith most often (Zhang, 2024). The top 3 of vessel types passing is closed with M9 vessels. M9 and M8 vessels have the same linear relation between the vessel draught and the loading factor. Therefore, it has been chosen to include M8 vessels in the model. The smaller vessels of types M6, M4 and M2 vessels are included in the model as well. The vessels departing from Rotterdam are determined in the shipments. The effective loading capacity is affected by the maximum available draught of that section in the river.
3. As the IVS data includes transported weight instead of numbers of containers, the model focuses on transported weight (measured in tons) as well. A conversion factor of 8.95 ton/TEU is used to converge parameters where needed (Bal, F., Vleugel, J.M., 2023). For instance, the handling capacity of a terminal crane is converted to tons/hour using this factor.
4. The transportation network is known. The nodes are fixed and modality availability in the nodes is covered in the network by creating arcs that allow for a transport modality if the terminal has access to certain infrastructure. As the nodes are fixed, the transportation distances are known. All transportation distances on the arcs are Euclidean distances based on the actual coordinates of the nodes. Because of the Euclidean distance, the distance by truck and train is equal from a terminal to the destination. The final destination of a shipment is, regardless if the last modality is road or rail transport, a rail yard.
5. In a node, different modes of transport can be chosen for a certain shipment. Part of the shipment can, for instance, be transported by M8 vessel and another part can be transported by M2 vessel. Cargo of different shipments cannot be consolidated on vessels, meaning that there is only one shipment with one destination per vessel.
6. Shifting cargo can only be done in a node where infrastructure and facilities are available to handle the cargo. This can be done in a terminal, a potential new hub, or a terminal that is selected for extension. If an extended terminal is selected, the original, non-extended terminal cannot be used. Transfer costs are included as a fixed cost per hour per modality, which are derived from Van der Meulen et al. (2023).
7. The potential new hubs and extensions of existing terminals differ in establishment costs. The establishment costs for a terminal that is already operational and requires no modifications are considered zero. However, extension of existing terminals is also possible.

8. Storage and handling capacities vary between the terminals. Handling capacity is reflected in the number of container cranes available on the quays. In this model, storage capacity is considered in the handling capacity, because the model does not simulate time steps. When considering storage capacity of a terminal, inventories of containers and arrivals of vehicles should also be included which would increase the model complexity. Besides, cost figures of German inland terminals showed that costs for storage will be charged after a 2 days period of freetime and the average storage time of cargo in inland terminals is generally shorter than 2 days.
9. The model aims to minimize total transport costs, which includes the fixed vehicle costs, variable transport costs, transshipment costs and daily hub establishment costs. Although these costs are charged to shippers, a budget for daily hub establishment costs is not considered, because the model aims to minimize the total costs in the theoretical optimal situation. Using a budget can shift the results to a local optimum which does not optimize the minimization of total costs. However, if the model is used by terminal owners and shipping companies, a slight adjustment can include a constraint on a budget.
10. Although the maximum capacity and effective capacity of a vehicle of a certain modality is taken into consideration, it is assumed that there are unlimited trucks, trains, and vessels of each type available. Unlimited availability of trains is not realistic. The impact of this will be evaluated in the scenario-based analysis by constraining the rail capacity with the amount of cargo that is transshipped to rail in the model under normal river discharge conditions.
11. The origin-destination data originates from data that is collected by Rijkswaterstaat in Lobith (a region upstream Nijmegen). Lobith is the place where the Rhine enters the Netherlands from the German border. This includes only measurements of cargo in the network that is being transported by waterway transport. Therefore, cargo has to leave the Port of Rotterdam by waterborne transport. The impact of this will be evaluated in the scenario-based analysis.
12. The origin and destination of the transported weight is used to route the cargo through the network. The destinations in the IVS data were clustered to the closest rail yard of the Deutsche Bahn. These yards are the final destination of the cargo in the model. The rail yard is in the real-world not the final destination. In the real-world, there would be additional costs for another transshipment to truck for last-mile transport. In the model, since the rail yard is the final destination, trucks also drive to the rail yards.
13. Because the model only focuses on port-hinterland transport, only 54% of the terminal capacity is allocated for port-hinterland transport (Port of Rotterdam, n.d.-a).
14. Time (e.g. waiting time to (un)load, or sailing time) is not considered in the model. The time it takes to (un)load cargo is only used to determine the costs for (un)loading.
15. Due to a lack of river discharge data at other points in the Rhine river, the river discharge measured at Lobith and the corresponding water levels in the Rhine river have been used to compute the water levels in different river discharge scenarios. The relation between the water level and the river discharge level has been linearized for this.
16. External factors such as disruptions due to weather are not included in the model.

Table 5.2: Sets and indices, decision variables and parameters of the hub selection formulation.

Sets and indices		
F	Set of shipments that have to be send from the origin to the destination	
$O \subset T \subset N$	Origin (Rotterdam, node 1)	
$N1 \subset T \subset N$	CTU Tiel (node 2)	
$D \subset N$	Set of destinations where d_f is the destination d of shipment f	
T	Set of all terminals along the Rhine river that allow for modality shift of containerized transport	
$H \subset T \subset N$	All potential hub locations (16 options) along the Rhine river There are 3 locations for potential new hubs that have multiple size options: $H_1 \subset H$ = hub options for Homberg location $H_2 \subset H$ = hub options for Koblenz Raptors location $H_3 \subset H$ = hub options for shunting yard location	
$P \subset T \subset N$	Existing terminals of which the size can be extended There is one terminal that can be extended with different sizes: $P_1 \subset P$ = extending options for terminal BCTN Nijmegen	
N	Set of nodes, $i, j \in N$ i represents forward node, j represents backward node	
K	Set of transportation modes. $k, l \in K$ (1 = M8 vessel, 2 = M6 vessel, 3 = M4 vessel, 4 = M2 vessel, 5 = train, 6 = truck)	
V_k	Set of vehicles of modality k. $v_k \in V_k$	
E	Set of admissible edges (i, j) in E	
Decision variables		**Unit**
$z_{ij}^{f d_f k v_k}$	weight cargo of transshipment f for destination d_f transported by vehicle v_k of mode k from node i to j	Ton
$d_t^{f d_f k v_k}$	vehicle specific change in weight of cargo of shipment f for destination d_f shifted from vehicle v_k of mode k in terminal t	Ton
S_t	1 if terminal t is selected for extension/establishment, 0 otherwise	{0,1}
$\delta_{f d_f}^{v_k}$	1 if vehicle v_k of modality k is used for shipment f to destination d_f	{0,1}
Parameters		**Unit**
FC_k	Fixed vehicle costs for using a vehicle of modality k	EUR/vehicle
C_k	Transport costs per ton-km using transport modality k	EUR/ton-km
CE_t	Time equivalent terminal establishment/extension costs of terminal $t \in H \cup P$	EUR/day
d_{ij}^k	Distance between node i and node j using mode k	Kilometer
CT_k	Costs per hour to (un)load cargo of modality k	EUR/hour
$d_{\text{abs},t}^{f d_f k v_k}$	absolute value of vehicle specific change in weight of cargo of shipment f for destination d_f shifted from vehicle v_k of mode k in terminal t	Ton
cap_k	Vehicle capacity of mode k	Ton/trip
cap_t	Daily handling capacity of container terminal t (or potential hub h or extended terminal p which are subsets of T)	Ton/day
$q_{v_k}^{f d_f}$	Initial loading of shipment f for destination d_f transported weight by vehicle v_k	Ton
$draught_{ij}^{max}$	Maximum draught from node i to j	m
$draught_{empty}^{k}$	Empty draught of modality k for $k \in \{1, 2, 3, 4\}$	m
$draught_{\text{vessel}}^{k,\text{LF}}$	Vessel draught of vessel type $k \in \{1, 2, 3, 4\}$ given the loading factor LF	m
$draught_{diff}^{k}$	Difference in empty and loaded draught for modality k for $k \in \{1, 2, 3, 4\}$	m
$LF_{\text{max},ij}^{k}$	Maximum loading factor of transport mode $k \in 1, 2, 3, 4$ (vessel types only) on arc i, j given the available draught	-
cap_{eff}^{kij}	Effective capacity of modality $k \in 1, 2, 3, 4$ (vessel types only) on arc i, j given the available draught	Ton
v_{load}	Loading rate of a container crane	Ton/hour
RC	Available capacity of the rail freight network	Ton
H_{max}	Maximum number of new hubs h to be established	-
P_{max}	Maximum number of existing terminals p that can be extended	-
ϵ	Small value to activate arc flow	-
M	Big M, large value	-

5.3.2. Relation between different parameters

The available draught ($draught_{ij}^{max}$) is based on the actual water level, the guaranteed depth at the Agreed Low River discharge level, the equivalent water level and the under keel clearance.

Figure 5.6 visualizes the relation between the available draught, actual water level, equivalent water level, guaranteed depth and under keel clearance. From this visualization, the available draught can be computed as shown in Equation 5.1.

$$\text{Available draught} = \text{guaranteed depth} + \text{actual level} - \text{equivalent level} - \text{under keel clearance} \quad (5.1)$$

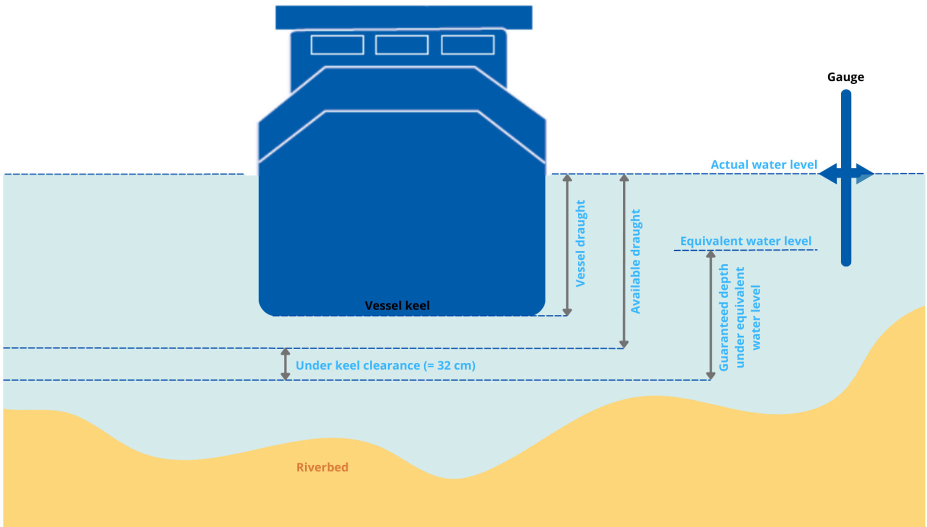


Figure 5.6: Relation between the available draught, actual water level, equivalent water level, guaranteed depth and under keel clearance.

The guaranteed river depth varies from 1.90 meters to 3.00 meters. The equivalent water levels are agreed values which are determined in 2022 (CCNR, n.d.). The guaranteed depth and the corresponding equivalent water levels at different gauge stations in the river can be seen in Table 5.9. The under keel clearance can vary for each vessel in reality, but in this research it is fixed to 32 centimeters (CCNR, n.d.). The guaranteed depth and other characteristics of the Rhine river at Agreed Low River discharge can be found in Appendix C.

Table 5.9 shows an example of computing the available draught using Equation 5.1 when the river discharge at Lobith was 1063 m^3/s (measured on 14 April 2025). The actual water level varies every day and had to be found on the websites of Rijkswaterstaat and Elwis for the corresponding river discharge at Lobith (Elwis, n.d.; Rijkswaterstaat, n.d.). Table 5.9 is only an example to show the relation between the available draught and the guaranteed depth, equivalent water level actual water level and under keel clearance. More details on determining the available draught for the different river discharge levels as used in this research will be provided in section 5.3.4. Parameters.

Table 5.3: Maximum draught based on water levels of 14 April 2025, 13.00 and a water discharge of 1063 m^3/s at Lobith (Elwis, n.d.; Ministerie van Infrastructuur en Waterstaat, 2024)

Gauge station	Guaranteed depth	Equivalent water level	Actual water level Q=1063 m^3/s	Available draught Q = 1063 m^3/s
Druten	280	255	368	361
Lobith	280	516	736	468
Duisburg	280	227	240	261
Köln	250	139	143	222
Kaub	190	77	79	161
Maxau	210	372	361	167
Basel	300	501	499	267

The available draught is related to the loading of the vessel. In the literature it was found that a linear relation between the draught of a vessel and the loading factor can be identified. Equation 4.3 showed that the loading factor is a factor that indicates what part of the vehicles capacity is used to transport cargo.

Figure 5.7 shows that the vessel has an empty draught ($draught^k_{empty}$) when there is no cargo loaded to the vessel. The vessel draught increases when cargo is loaded to the vessel because the loading factor increases. If the vessel is loaded up to the full capacity, the vessel draught equals the fully loaded draught ($draught^k_{loaded}$). The difference between the loaded and empty draught ($draught^k_{diff}$) affects the vessel draught based on the vessel loading factor. There is a linear relation between the empty draught, difference between the loaded and empty draught and the loading factor to compute the vessel draught. This can be seen in Equation 5.2. The values of these terms are specified in Table 5.4. The vessel draught cannot exceed the available draught in a section of the river to avoid the risk of grounding (Equation 5.3).

If the available draught is smaller than the loaded vessel draught, the effective capacity of the vessel is affected because the loading factor must be less than 1. The maximum loading factor can be computed by Equation 5.4. $draught^{\max}_{ij}$ is the available draught in a section of the river. The division of factors is a result of rewriting Equation 5.2. The effective capacity is vessel and link specific and can be computed by multiplying the maximum loading factor of a vessel on the link from i to j with the capacity of the vessel type as shown in Equation 5.5.

$$draught^{k,\mathrm{LF}}_{\mathrm{vessel}} = draught^k_{\mathrm{empty}} + draught^k_{\mathrm{diff}} \cdot LF \tag{5.2}$$

$$draught^{k,\mathrm{LF}}_{\mathrm{vessel}} \leq draught^{max}_{ij} \tag{5.3}$$

$$LF^k_{\mathrm{max},ij} = \min\{1, \frac{draught^{max}_{ij} - draught^k_{\mathrm{empty}}}{draught^k_{\mathrm{diff}}}\} \tag{5.4}$$

$$cap^{kij}_{\mathrm{eff}} = cap_k \cdot LF^k_{\mathrm{max},ij} \tag{5.5}$$

Table 5.4: Linear relations between draughts and loading factor of the vessel types in the IVS data.

RWS type	Linear relation
M2	1.40 + 1.20 * loading factor
M4	1.50 + 1.10 * loading factor
M6	1.00 + 1.90 * loading factor
M8	1.80 + 1.70 * loading factor

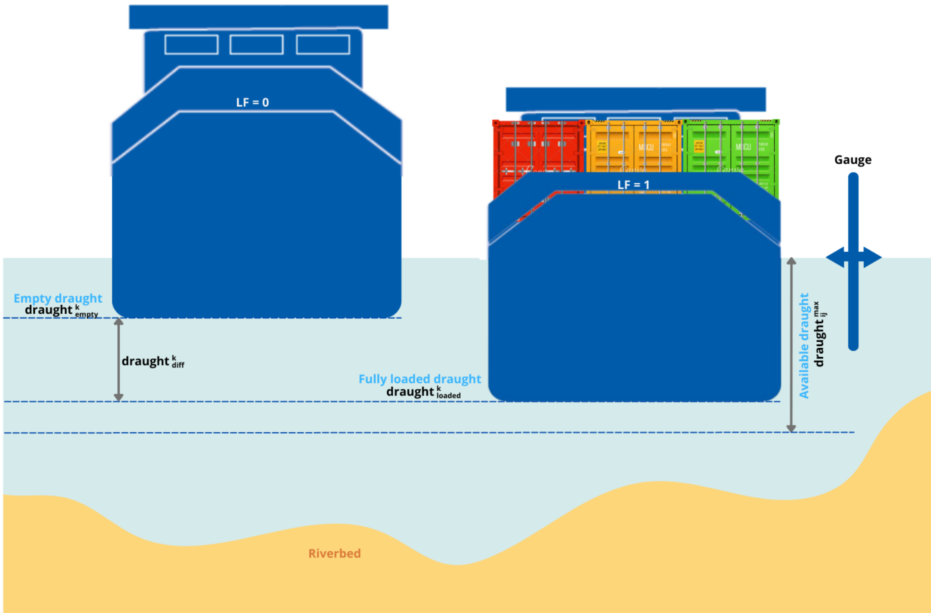


Figure 5.7: Relation between the vessel loading, the vessel draught and the available draught.

5.3.3. Model formulation

The objective function aims to minimize the total fixed vehicle costs for using a vehicle, the variable transportation costs, the transfer costs, and the time equivalent (daily) hub establishment and terminal extension costs.

The objective function can be formulated as follows:

$$\min Z = \sum_{f\in F}\sum_{k\in K}\sum_{v_k\in V_k} FC_k \delta^{v_k}_{fd_f} + \sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V}\sum_{(i,j)\in E} z^{fd_fkv_k}_{ij} c^k d^k_{ij} + \frac{\sum_{f\in F}\sum_{d_f\in D}\sum_{k=1}^{4}\sum_{v_k\in V}\sum_{t\in T\setminus\{O\}} d^{fd_fkv_k}_{abs,t} CT_k}{v_{\text{load}}} + \sum_{f\in F}\sum_{d_f\in D}\sum_{k=5}^{6}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in D} \frac{z^{fd_fkv_k}_{ij} CT_k}{v_{\text{load}}} + \sum_{t\in H\cup P} CE_t S_t \tag{5.6}$$

The first term in the objective function represents the fixed vehicle costs. For each vehicle that is needed for transport, a fixed cost has to be paid. Therefore, this cost term has to be considered for all vehicles of all modality used to transport cargo.

The second term represents the variable transport costs. For each modality, a variable cost term in euro per ton-kilometer is used. To compute the total transport cost over all shipments, the cost factor has to be multiplied by the transported weight of each vehicle of each modality on each link and the distance of the corresponding links.

The third and fourth term of the objective function represent the transfer costs. The transfer cost consist of intermodal and intra-modal transfer costs. For intermodal transfers, cargo has to be unloaded of one modality to be loaded on another modality. The (un)loading costs are measured in euro per hour. The time needed to (un)load cargo is based on the cargo to reload and the handling capacity of the crane (the crane rate). The total costs for shifting modality consist of unloading of the vessel and loading to another vehicle or another modality. Note that shifting to another vessel type is also considered as a modal shift.

The change in cargo carried by a vessel is captured in $d_{abs,t}^{fd_fkv_k}$. $d_{abs,t}^{fd_fkv_k}$ captures all changes in the vessel weights in the container terminals (including potential new hubs and extended terminals) along the river. Therefore, the third term captures unloading and loading of vessels. Transfers to train and truck are considered in the fourth term. If cargo is loaded to a train or truck, it is headed directly to the final destination without intermediate transshipments. Therefore, all flows on trains and trucks have to be captured in the transfer costs. The cost factors for (un)loading are provided in euro/hour. Therefore, the weight that shifts modality has to be divided by the speed of the crane in ton/hour. This has to be multiplied by the cost factor. It is not realistic to assume that cargo directly shifts from one vehicle to another. In real-world operations, it is stored in the terminal first before being loaded to another vehicle. However, storage costs in the terminal have been left out. Cost figures of costs in German inland terminals have shown that storage costs are 50 euro per day per TEU after 2 days of freetime. The average storage time of cargo in inland terminals is generally shorter than 2 days. Besides, the model does not simulate in time steps, which would require inventory tracking in terminals as well. Therefore, costs for storing cargo in the terminals have not been considered in this model.

The fifth term of the objective function represents the time equivalent (daily) hub establishment and terminal extension costs. The hub establishment and terminal extension costs vary according to if the new hub or existing terminal requires modifications or total establishment, and the size of the modifications or establishment. Hub establishment costs are only considered if the hub is selected to be established. This is the same with extension costs of terminals that are selected to be extended. The time equivalent hub establishment or terminal extension costs are based on a lifetime fo 25 years. For terminals that exist longer than 25 years, the time equivalent establishment costs are considered 0.

The objective function is subject to a set of constraints.

Flow conservation: an important aspect of routing optimization models are the node flow conservation constraints. These constraints ensure that all cargo of all shipments leaves the source flow, all demand enters the demand node (destination), and in hubs and terminals (intermediate nodes) all cargo coming into the node is also leaving the node. The flow conservation has to be balanced for all cargo entering and leaving the node and is tracked based on the shipments.

Source outflow: in the model, cargo has to be transported from the Port of Rotterdam (source) to different destinations. Each vessel has to transport cargo of a shipment with its own destination (which can also be seen in the IVS data). The cargo can only leave the source node by vessel (modalities 1, 2, 3, 4), as all data points in the IVS data were measured on the water at Lobith. For each shipment, a predetermined vessel departs with a predetermined amount of cargo and destination.

$$z_{ij}^{fd_fkv_k} = q_{v_k}^{fd_f}, \forall f \in F, d_f \in D, k \in \{1,2,3,4\}, v_k \in V, i \in O, j \in N1 \tag{5.7}$$

Transport to the destination: the model allows transport to the destination only via truck and train, as the destinations are rail terminals of the Deutsche Bahn. These rail terminals are not located directly near the Rhine river. Therefore, the cargo cannot reach the destination by waterborne transport. The inflow at a destination of a shipment f should equal all flows over all vehicles from trucks and trains carrying a specific shipment.

$$\sum_{k \in K} \sum_{v_k \in V} \sum_{i \in T} z_{ij}^{fd_fkv_k} = q_{v_k}^{fd_f}, \forall f \in F, d_f = j, k \in \{5,6\}, v_k \in V, j \in D \tag{5.8}$$

Transport in intermediate nodes: in intermediate nodes (existing terminals except the origin, extended terminals and potential new hubs) all cargo of a certain shipment that comes in a node also has to leave the node. The total flow in all vehicles of all modalities that transport cargo of shipment f into a terminal must equal the total flow in all vehicles in all modalities that transport cargo of shipment f for destination d_f out of the terminal.

$$\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in T\setminus\{O\}} z_{ij}^{fd_fkv_k} = \sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in T\setminus\{O\}} z_{ji}^{fd_fkv_k}, \forall f \in F, d_f \in D \tag{5.9}$$

Transshipments in the terminals: transfers occur in the terminals (including selected new hubs and extended terminals). Because the Rhine river is simulated as links between existing terminals, vessels can sail past terminals without using them, which shows no change in the flow in a vehicle. Therefore, cargo of a shipment can stay in its mode and vehicle or it can shift to an empty vehicle (a shallower draught vessel or a truck or train). To measure modality shifts, the flow in each vehicle leaving a terminal is compared to the flow in a vehicle entering the terminal. This way, both increases and decreases in the cargo of a shipment carried by a vehicle of a certain modality are captured in $d_n^{dkv_k}$. Because a decrease of the flow in a vehicle is negative, the absolute value of this variable should be used when calculating the costs for transfers. This is linearized in Equation 5.11.

$$d_t^{fd_fkv_k} = z_{it}^{fd_fkv_k} - z_{tj}^{fd_fkv_k}, \forall f \in F, d \in D, k \in \{1,2,3,4\}, v_k \in V, t \in T, (i,t) \in E \tag{5.10}$$

$$\text{Where: } d_{\text{abs},t}^{fd_fkv_k} \geq -d_t^{fd_fkv_k} \text{ and } d_{\text{abs},t}^{fd_fkv_k} \geq d_t^{fd_fkv_k} \tag{5.11}$$

Assign only one shipment to a vehicle: each vehicle can only carry one shipment f for destination d.

$$\sum_{f\in F} \delta_{fd_f}^{v_k} = 1, \forall v_k \in V, d_f \in D \tag{5.12}$$

Preserve final destination: during transshipment it should be ensured that the final destination of the shipment is preserved. This is done by forcing the flow to be zero if the destination of the flow does not correspond to the predetermined destination of the shipment.

$$z_{ij}^{fdkv_k} = 0, \forall f \in F, d \in D \setminus \{d_f\}, k \in K, v \in V_k, (i,j) \in E \tag{5.13}$$

Terminal capacity: transshipments in terminals cannot exceed the handling capacity of a terminal. When cargo switches from vessel to truck or train, the cargo has to be unloaded of the vessels by the ship-to-shore crane. When cargo has to be reloaded from one vessel to another, the cargo is first loaded to the quay and then loaded to another vessel. These operations are all captured in $d_{\text{abs},t}^{dkv}$ since it tracks the change in cargo of each individual vessel. The total operations in existing terminals and cannot exceed the daily terminal capacity (Equation 5.14. For potential new hubs and terminals to extend, the capacity of the selected new hubs and extended terminals cannot exceed the handling capacity of the terminal (Equation 5.15).

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V} d_{\text{abs},t}^{fd_fkv_k} \leq \text{cap}_t, \forall t \in T \setminus \{H \cup P\} \tag{5.14}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V} d_{\text{abs},t}^{fd_fkv_k} \leq \text{cap}_t S_t, \forall t \in H \cup P \tag{5.15}$$

$$\tag{5.16}$$

Limit flow over rail: in the different scenarios, the flow transported by rail transport will be limited by the available capacity of the rail freight network. Therefore, the amount of cargo transported over the rail cannot exceed the capacity of the network.

$$\sum_{i\in T}\sum_{j\in D}\sum_{f\in F}\sum_{v_k\in V} z_{ij}^{fdkv_k} \leq RC, \forall k=5, d_f=j \tag{5.17}$$

Hub and terminal flow: flow via the hub is only allowed if the hub is selected (Equation 5.18. Flow via an extended terminal is also only allowed if the terminal is selected for extension. If that is the case, then flow handling in the original terminal is not allowed anymore (Equation 5.19).

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in H\cup P} z_{ij}^{fd_fkv_k} \leq MS_t, \forall t=j \tag{5.18}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{t\in P} z_{ij}^{fd_fkv_k} \leq M(1-S_t), \forall j=t\in T \tag{5.19}$$

Effective capacity of vessels: bottlenecks are incorporated in the model by adding the maximum draught to each waterway link. The maximum draught affects the maximum loading of each vessel of each vessel type. The flow assigned to each vessel cannot exceed the effective capacity on a vessel of modality k.

$$z_{ij}^{fd_fkv_k} \leq cap_k LF^k_{\max,ij}, \forall f\in F, d_f\in D, k\in\{1,2,3,4\}, v_k\in V, (i,j)\in E \tag{5.20}$$

Establishment and extension selection: the maximum number of new established hubs can be limited (Equation 5.21) as well as the maximum number of extended terminals (Equation 5.22. This is useful for the cases which simulate transport in the existing network, then S_h is forced to be 0. For the same reason, the number of extended terminals can be limited as well. By forcing S_h to be 0, the results are based on the existing terminals only, which is useful to analyze the impact of hubs by comparing the results where hubs are established and used. Costs for establishment and extension are considered in the objective function A budget constraint could have been added, but was chosen not to. The objective is to minimize total costs for transporting the shipments which are not necessarily paid by one stakeholder. Although the costs are charged to shippers, a budget would be useful if the cost minimization was done from the perspective of terminal owners which have a budget for establishing new terminals.

$$\sum_{h\in H} S_h \leq H_{\max} \tag{5.21}$$

$$\sum_{h\in P} S_h \leq P_{\max} \tag{5.22}$$

Multiple size options for one location: in the list of potential hubs, there are some locations that have multiple options for the size of a new hub. At most one of the size options for such a location can be selected. This is also the case for terminal extension, because the terminal BCTN Nijmegen has two options for extension.

$$\sum_{t\in H_1} S_t \leq 1 \tag{5.23}$$

$$\sum_{t\in H_2} S_t \leq 1 \tag{5.24}$$

$$\sum_{t\in H_3} S_t \leq 1 \tag{5.25}$$

$$\sum_{t\in P_1} S_t \leq 1 \tag{5.26}$$

Domains of the variables: Lastly, the domains of the decision variables have to be specified. S_t and $\delta^{v_k}_{fd_f}$ are binary decision variables. $z^{fd_fkv_k}_{ij}$ cannot be negative. $d^{fd_fkv}_{\text{abs},t}$ is the absolute value of $d^{fd_fkv}_t$ and can therefore not be negative.

$$S_t \in \{0,1\}, \forall t \in H \cup P \tag{5.27}$$

$$\delta^{v_k}_{fd_f} \in \{0,1\}, \forall v_k \in V, f \in F, d_f \in D \tag{5.28}$$

$$z^{fd_fkv_k}_{ij} \geq 0, \forall f \in F, d_f \in D, k \in K, v_k \in V, (i,j) \in E \tag{5.29}$$

$$d^{fd_fkv_k}_{\text{abs},t} \geq 0, \forall f \in F, d_f \in D, k \in K, v_k \in V, t \in T \tag{5.30}$$

5.3.4. Parameters

This section describes the values of the parameters used in the base model.

Demand

From the data analysis it was found that dropping water discharge levels result in a decrease in transported cargo. However, in order to compare the results of the different scenarios later on equally, the same shipments have to be routed through the network. The shipments to route through the network are derived from the IVS data. Using a day where the river discharge is 1400 m^3/s would overestimate the amount of cargo passing Lobith when the river discharge is 1020 m^3/s which was also shown in chapter 4. Therefore, it is chosen to use shipments measured on a day where the river discharge is between 1010 and 1030 m^3/s through the network in each scenario, including the base model. The shipments are based on IVS data of 27 November 2021 where the discharge level is around 1020 m^3/s. More details on why the selection of the shipments is chosen is described in Appendix D.

The demand that has to be transported from the origin Rotterdam to the destinations in the network can be seen in Table 5.5.

The destination as provided in Table 5.5 is a result from clustering the destinations in the data to the rail yards of the Deutsche Bahn. The initial IVS data did not contain RWS labels. Therefore, all vessels in the data were labeled with an RWS type. This model includes vessels of RWS type M2, M4, M6 and M8. The loading factor is derived from the IVS data by dividing the loading by the capacity as previously shown in Equation 4.3. However, because the loading capacities in the IVS data sometimes exceed capacities as specified by Vinke et al. (2024), the loading for each shipment is calculated by multiplying the loading factor and the transport capacity of the vessel as specified in Table 5.7.

The vessels leaving the source node and the corresponding vessel types and loading factors were derived from the IVS data. For this, days with a discharge between 1010 and 1030 m^3/s have been observed and it was chosen to simulate the vessels measured in Lobith on 27 November 2021. On this day, the transported weight was highest and this day contained 33 shipments for 6 destinations which more interesting compared to the other days with less shipments and less destinations.

Table 5.5: Shipment specifications of vessels departing from Rotterdam.

Shipment	Destination	Vessel type	Loading factor
0	Oberhausen	M8	0.20
1	Oberhausen	M8	0.19
2	Oberhausen	M8	0.20
3	Oberhausen	M8	0.38
4	Oberhausen	M4	0.39
5	Mannheim	M2	0.21
6	Mannheim	M6	0.29
7	Hagen	M6	0.65
8	Basel	M8	0.01
9	Oberhausen	M2	0.60
10	Seelze	M2	0.87
11	Oberhausen	M4	0.34
12	Oberhausen	M4	0.45
13	Oberhausen	M6	0.66
14	Basel	M8	0.01
15	Mannheim	M2	0.22
16	Mannheim	M6	0.32
17	Mannheim	M2	0.32
18	Mannheim	M6	0.47
19	Basel	M4	0.37
20	Oberhausen	M4	0.37
21	Oberhausen	M2	0.74
22	Oberhausen	M2	0.67
23	Köln Gremberg	M4	0.40
24	Mannheim	M6	0.37
25	Oberhausen	M4	0.45
26	Mannheim	M2	0.27
27	Köln Gremberg	M4	0.42
28	Mannheim	M2	0.32
29	Oberhausen	M8	0.46
30	Oberhausen	M4	0.40
31	Basel	M4	1.00
32	Mannheim	M6	0.42

Table 5.6 shows the total weight that has to be transported to each destination based on all shipments in Table 5.5. The shipments include 6 unique destinations. In total 16759.0 ton will be shipped from Rotterdam departing in 33 vessels.

Table 5.6: Mean daily weight of cargo that has to be transported to the rail yards based on the clusters.

Origin	Destination	Transport weight in tons
Rotterdam	Seelze	570.0
	Oberhausen	8,667.0
	Mannheim	4,120.0
	Köln	822.0
	Hagen	1,133.0
	Basel	1,447.0
Total		16,759.0

Costs

Variable transport costs and transshipment costs

The transport costs per ton per kilometer for M2, M6, M8, trucks and trains are derived from research by Van der Meulen et al. (2023). M4 vessels are also included in the model, but since the report by Van der Meulen et al. (2023) only included M2, M6 and M8 vessels, the cost figures for M4 vessels have been estimated based on the cost figures of the other vessel types. For this estimation, economies of scale have been considered, so the transport costs per ton-kilometer of an M4 vessel should be less than costs for transport by an M2 vessel, but more than transport costs of an M6 vessel. The cost factors by Van der Meulen et al. (2023) include variable costs, staff costs, mode specific and general operating costs.

Table 5.7 gives an overview of the average capacities, transport costs and (un)loading costs for different sizes of vessels, a freight train and a truck (Van der Meulen et al., 2023).

Table 5.7: Specification of the transport costs and (un)loading costs per transport modality (Reporting, n.d.; Van der Meulen et al., 2023).

Transport modality	Average capacity [tonne]	Transport costs [EUR/tonnekm]	(Un)Loading costs [EUR/h]
M2 vessel	655	0.092	41.30
M4 vessel	1000	0.064	54.75
M6 vessel	1750	0.036	68.19
M8 vessel	2750	0.025	105.23
Freight train	390	0.045	462.17
Truck	17.9	0.125	43.45

Fixed vehicle costs

Besides the variable transport costs per ton per kilometer, the model includes fixed costs for adding another vehicle. These fixed costs are computed based on break-even distances. Zgonc et al. (2019) investigated the impact of distance on mode choice in freight transport and found a break even distance of 248 kilometer for truck and train. This means that the costs for transport by train and truck are equal at a distance of 248 kilometer. The average cost of €11,577 per train was considered as the fixed costs for trains (Zgonc et al., 2019). The transport cost per ton per kilometer from Table 5.7 was used as the variable costs for transporting 390 ton over 248 kilometer. The break-even balance for computing the fixed vehicle costs of trucks and trains can be seen in Equation 5.31. Here it should be noted that the capacity of a train (390 ton) can be transported with 22 trucks. The fixed cost per truck can then be derived by Equation 5.33.

$$FC^{tot}_{\text{truck}} + C_{\text{truck}} \cdot z^{dkv_k}_{ij} \cdot d^k_{ij} = FC_{\text{train}} + C_{\text{train}} \cdot z^{dkv_k}_{ij} \cdot d^k_{ij} \tag{5.31}$$

$$FC^{tot}_{\text{truck}} + 0.125 \cdot 390 \cdot 248 = 11577 + 0.045 \cdot 390 \cdot 248 \tag{5.32}$$

$$FC^{tot}_{\text{truck}} = \frac{3839.40}{22 \text{ trucks}} \tag{5.33}$$

Lu and Yan (2014) investigated the break-even distance of road and inland waterway freight transportation systems. The following break-even distances are used: for M2 vessels 110 kilometer, for M4 vessels 138 kilometer, for M6 vessels 166 kilometer and for M8 vessels 195 kilometer. The fixed vehicle costs for each vessel type is computed by Equation 5.34. For vessels, the average loading factor is considered of Van der Meulen et al. (2023) to correct for sailing with less cargo than the full transport capacity. The fixed vehicle costs can be seen in Table 5.8.

$$FC^{tot}_{\text{truck}} + C_{\text{truck}} \cdot z^{dkv_k}_{ij} \cdot d^k_{ij} = FC_{M2} + C_{\text{M2}} \cdot z^{dkv_k}_{ij} \cdot d^k_{ij} \tag{5.34}$$

$$FC^{tot}_{\text{truck}} = FC_{\text{truck}} \cdot \frac{cap_{M2} \cdot LF^{avg}_{M2}}{cap_{\text{truck}}} \tag{5.35}$$

$$FC^{tot}_{\text{truck}} = 174.52 \cdot \frac{655 \cdot 0.14}{17.9} = 3530 \tag{5.36}$$

$$3530 + 0.125 \cdot 92 \cdot 110 = FC_{M2} + 0.092 \cdot 92 \cdot 110 \tag{5.37}$$

Table 5.8: Fixed costs per vehicle of each modality. The average loading factors are derived from the average tonnage divided by Van der Meulen et al. (2023).

Modality	Average loading factor	Fixed cost per vehicle FC_k
M2 vessel	0.14	2600
M4 vessel	0.17	3175
M6 vessel	0.19	8220
M8 vessel	0.17	21500
Train		11577
Truck		174.52

Available draught

The base model will be based on normal river discharge, which equals 1400 m^3/s discharge in Lobith (Rijkswaterstaat, n.d.). In this research, it is assumed that the relation between river discharge and water level is linear. Therefore, based on two different days, measurements on the river discharge level at Lobith and corresponding water level in different gauge stations were done to compute the actual water level at each gauge station for the river discharge of 1400 m^3/s. Based on this, and using Equation 5.1, the available draught at the different gauge stations could have been computed, which is shown in Table 5.9. More details on how the relation between river discharge and water level was linearized, can be found in Appendix C.

Table 5.9: Overview of the available draught on different sections of the river when river discharge at Lobith is 1400 m^3/s. The gauge stations represent the sections. From Rotterdam to Druten, from Druten to Lobith, and so on.

Gauge station	Available draught Q = 1400
Druten	431
Lobith	540
Duisburg	327
Köln	289
Kaub	231
Maxau	264
Basel	321

Effective loading capacity

The maximum draught affects the effective loading capacity in different sections of the river. The effective loading capacity for all vessel types in different river sections in the base model when river discharge at Lobith is 1400 m^3/s can be seen in Table 5.10.

Table 5.10: Effective loading of different vessel types in different sections of the river when the river discharge at Lobith is 1400 m^3/s.

Gauge station	Available draught Q=1400	M2	M4	M6	M8
Druten	655	1000	1750	2750	
Lobith	655	1000	1750	2750	
Duisburg	655	1000	1750	2378	
Köln	655	1000	1654	1763	
Kaub	497	736	1146	825	
Maxau	655	1000	1435	1359	
Basel	655	1000	1750	2281	

Handling capacity

The handling capacity is determined by the number of container cranes available on the quays to load and unload cargo from vessels.

To determine the handling capacity of a terminal, the crane rate has to be determined, which is the movements per hour of ship-to-shore cranes. The movements per hour of a ship-to-shore crane depend on different factors. An example is automation, which increases the movements per hour. In order not to overestimate the hourly rate of a crane, the minimum movements per hour have been used. Research by Zrnic et al. (2005) has found a minimum of 30 movements per hour, which is in line with other research that found an average of 2 minutes per movement (Jachimowski & Kłodawski, 2025). The 30 movements are based on 1,75 TEU per movement. This results in an hourly crane capacity of 470 ton/hour.

6

Results Base Model

In this chapter, the results from the optimization model as described in section 5.3 will be provided. The base model simulates routing of the shipments through the current system with normal discharge levels. This model simulates routing of the shipments based on a water discharge of 1400 m^3/s, which is determined as 'normal river discharge' by Rijkswaterstaat (n.d.). From the results of this model, the current transport flows can be obtained as well as the total costs and CO_2-equivalent emissions of the transport and terminal utilization. From this model, the capacity of the rail network under normal circumstances is also obtained.

6.1. Results of the base model - river discharge 1400 m^3/s

From the base model, the cost breakdown can be seen in Table 6.1. New hubs cannot be established and existing terminals cannot be extended. Therefore, both of these cost terms are €0.00. The total cost is €1,021,043.92 which includes the fixed vehicle cost, the variable transport costs and the transfer costs.

Table 6.1: Cost breakdown of the base model at river discharge of 1400 m^3/s.

Total cost	**€1,021,043.92**
Fixed vehicle cost	€472,215.08
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€206,925.08
Transport cost	€525,874.50
Total transfer cost	€22,954.34
Hub establishment cost	€0.00
Terminal extension cost	€0.00

From the costs in Table 6.1, it can be seen that the fixed vehicle costs are 46.2% of the total costs. The fixed vehicle costs are divided in fixed costs for vessels and fixed costs for trucks and trains. The fixed costs for vessels equal the fixed costs for all vessels departing from Rotterdam. This indicates that no transshipments are done to other vessel types on the Rhine river. The variable transport costs are 51.5% of the total costs. Transfer costs take up 2.3% of the total costs. This includes unloading cargo from vessels and loading cargo to trucks and trains.

Table 6.2 shows the transfers in the existing terminals along the Rhine river. The transfers in these terminals are selected by the model to minimize the total costs. It can be seen that the full daily capacity of terminal Nordfrost Wesel is used. It should be noted that the daily capacity as indicated here is measured in ton/day and covers 54% of the total terminal capacity because the model only considers port-hinterland transport. It also shows that the most upstream terminal used for transshipment is Contargo Ginsheim, which is located about 85 kilometers upstream Kaub.

The total of the transferred weight in all terminals equals the amount of cargo that is sent into the network in the Port of Rotterdam. The results show that 1767 tons are transshipped to rail transport in Contargo Emmerich. From the terminals used for transshipments, Contargo Emmerich is the only terminal with access to rail. Transshipment to rail transport is only selected if it contributes to total cost minimization. Due to the high fixed costs for using an additional train, nearly the entire capacity of the vehicle must be used and the distance has to be greater than the break-even threshold to minimize costs compared to transport by truck. Therefore, it only makes sense for shipments with a destination far from the terminal of transshipment and with a great enough flow to be transshipped to rail transport. The total amount of cargo shifted to rail transport will be assumed as the daily available capacity for rail freight transport as the normal capacity level for building the scenarios later on.

Table 6.2: Transferred weight in the selected terminals and the corresponding terminal utilization when the river discharge at Lobith is 1400 m^3/s.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
BCTN Nijmegen	2760.1 ton	22.7%	2760.1 ton	-
Contargo Emmerich	1767.0 ton	14.5 %	-	1767.0 ton
Nordfrost Wesel	6086.9 ton	100%	6086.9 ton	-
UCT Dormagen	1955.0 ton	32.1%	1955.0 ton	-
Contargo Ginsheim	4190.0 ton	68.8%	4190.0 ton	-

Table 6.3 provides an overview of the shipments handled in each terminal. From these results, it can be seen that transshipment of some shipments is split over multiple transshipment terminals. This is, for instance, the case for shipment 10 to Seelze. Part of the cargo is unloaded in BCTN Nijmegen while another part is unloaded in Contargo Emmerich. The part that is unloaded in BCTN Nijmegen is the excess cargo that would exceed the capacity of a freight train. The unloaded cargo from other shipments in BCTN Nijmegen is cargo that could not be transshipped in Nordfrost wesel because it would exceed transshipment in Nordfrost Wesel would exceed the terminal capacity. Transshipment of cargo of shipment 12 for Oberhausen is also split over multiple terminals. Part of the cargo is transshipped in BCTN Nijmegen to reduce the vessel loading so that it complies with the available draught in the next sections of the river. It can also be seen that some cargo for Basel is unloaded in Contargo Emmerich while other shipments for Basel are unloaded in Contargo Ginsheim. This is a result from the loading on the vessel. The cargo of the heavier loaded vessels is transshipped in Contargo Emmerich to rail transport because there is sufficient cargo to fill up a train. The vessels with shipments for Basel that sail further to Contargo Ginsheim are loaded with a small amount of cargo. Therefore, to minimize total costs, this cargo is transshipped to trucks to be transported to Basel. It can be seen that the model aims to minimize total costs while complying to the available draught, terminal capacity and mode avaiability.

Table 6.3: Shipments handled in each terminal with the corresponding destination

Terminal	Shipment number for destination handled
BCTN Nijmegen	4 - Oberhausen 9 - Oberhausen 10 - Seelze 12 - Oberhausen 21 - Oberhausen 22 - Oberhausen 25 - Oberhausen
Contargo Emmerich	10 - Seelze 19 - Basel 31 - Basel
Nordfrost Wesel	0 - Oberhausen 1 - Oberhausen 2 - Oberhausen 3 - Oberhausen 11 - Oberhausen 12 - Oberhausen 13 - Oberhausen 20 - Oberhausen 29 - Oberhausen 30 - Oberhausen
UCT Dormagen	7 - Hagen 23 - Köln Gremberg 27 - Köln Gremberg
Contargo Ginsheim	5 - Mannheim 6 - Mannheim 8 - Basel 14 - Basel 15 - Mannheim 16 - Mannheim 17 - Mannheim 18 - Mannheim 24 - Mannheim 26 - Mannheim 28 - Mannheim 32 - Mannheim

Although minimization of the emission of CO_2-equivalent units was not an objective of the model, it is interesting to evaluate this indicator given minimization of the total costs. Table 6.4 shows the average CO_2-equivalent unit emission per ton-kilometer for each transport modality in the model. This emission is an average derived from Klein et al. (2021). Research by Klein et al. (2021) investigated the CO_2-equivalent unit emission of different transport modalities (including different vessel types) when the vehicle is loaded lightly loaded, medium-heavy loaded and heavy loaded. The average emission unit per ton-kilometer is a little higher than the medium-heavy loaded vehicles. That research shows that an increase in the vehicle loading results in a decrease of the CO_2-equivalent unit emissions per ton-kilometer (Klein et al., 2021).

The emission of trains is based on long trains with well-to-wheel emissions. For trains, there is a distribution where 73% of the freight trains are electric trains and 23% of the trains are diesel trains. The average CO_2-equivalent unit per ton-kilometer is based on this distribution.

The emissions of trucks were derived from trucks up to 20 tons with trailers (Klein et al., 2021). For these trucks, there are CO_2-equivalent units known for lightly loaded, medium-heavy loaded and heavy loaded trucks. For each category, the CO_2-equivalent unit is known for city, outer highways and highways. The CO_2-equivalent unit as shown in Table 6.4, the average is based on the three loading categories, only considering outer highways and highways. This was done, because the final destinations in the model (the rail yards of the Deutsche Bahn), are not located in city centers.

Table 6.4: Average CO_2-equivalent unit per transport modality in unit per ton-kilometer based on Klein et al. (2021).

Modality	Average CO_2-eq/tonkm
M2	18.30
M4	18.40
M6	19.57
M8	13.32
Truck	103.35
Train	20.08

These emission factors apply for each ton-kilometer of transport for each transport modality. Table 6.5 shows the transport performance in ton-kilometer of each transport modality and the total CO_2-equivalent emissions of the transport in the base model. It should be noted that the emissions of establishing new hubs or extending new terminals is not included here, as well as transshipment of cargo from one vehicle to another. Transportation at minimized cost in the base scenario results in emission of 258,379.20 kilograms CO_2-equivalent unit.

Table 6.5: Transport performance in ton-kilometer per transport modality in the base scenario where the river discharge at Lobith is 1400 m^3/s and the total CO_2-equivalent unit emission in kilograms.

Transport Modality	Q=1400
M2	951,305.7
M4	1,216,591.3
M6	2,940,538.1
M8	1,153,535.8
Truck	1,179,420.4
Train	1,184,287.7
CO_2-eq emission	258,379.20

The results, as shown above, show how the shipments are routed through the network in order to minimize total costs and the capacity utilization of the terminals used for transshipment. The results indicate the total costs for transporting all shipments and the corresponding CO_2-equivalent emissions of the transport. These results correspond to the base model and can be used as a benchmark for comparison of results in different scenarios. The results of the base model also indicated the capacity of the rail freight network under normal conditions, which will be the base for building scenarios.

6.2. Model verification

To verify that the model has been build correctly, some manual checks have been performed which can be seen in Appendix E. These manual checks verify the correct working of the constraints. The flow continuity of the shipments that are sent into the network from Rotterdam have to be verified from the source to the destination. The cargo of each individual shipment has to arrive at the destination. The shipment can be split over different vehicles along the routes but all cargo of a shipment has to arrive at the destination. The model's objective is to minimize the total costs so if at least 390 ton cargo has to be transported further than the break-even distance over land, the model has to choose for transport by at least one train. The vessel loading cannot exceed the effective capacity of the vessel given the available draught. It also has to be checked that the cargo handled in a terminal cannot exceed the terminals capacity. If it is allowed to select new hubs, at most one new hub of the subsets $H1$, $H2$, and $H3$ can be selected. Only if a hub is selected, the arcs from and to the selected hub can be used by vehicles and flow can be assigned to it. This also holds for extension of an existing terminal. If a terminal is selected for extension, the original terminal cannot be used anymore.

6.3. Sensitivity analysis

The sensitivity of the model to the parameters affecting the total costs of the optimized model has to be analyzed. Table 5 shows the results of the sensitivity analysis on the fixed costs for adding another vehicle of a certain modality, the transport cost per ton per kilometer of each modality, the transshipment costs, the vehicle capacities and the loading speed of the crane in the terminal. It shows the values of the parameters ranging from -50% to +50%. It also shows the percentage change of the total costs.

From Table 5 it can be seen that for most parameters the percentage change is, even with a 50% increase or decrease of certain cost parameters, relatively small. This is a result of the high total cost of the base model and the usage of the modalities. For the transport, the initial share of a certain vessel type is fixed. For the transport to the final destinations, a lot of trucks have to be used, while usage of rail transport is for a lot of shipments not economically viable. The more vehicles of a certain modality are used, the more sensitive the model becomes to a cost parameter for that modality.

It can be seen that the model is more sensitive to the fixed costs of M6 and M8 vessels. This is a result of the fact that the base parameter of the costs for M6 vessels is 3.1 times the fixed M2 cost and 2.6 times the fixed M4 costs. The base parameter of M8 vessels is 8.4 times the fixed M2 cost and 6.7 times the fixed M4 costs. From all the shipments, 21.9 % departs on a M6 vessel and another 21.9% departs on a M8 vessel. The model is more sensitive to the fixed costs for trucks compared to the fixed costs for trains. It can be seen that 50% increase or decrease of the fixed truck costs results in a 7.3% increase or decrease of the total costs. This is because for transport from the terminal to the destination, the distance is often too short to exceed the break-even distance threshold to transport the cargo by train. This makes it economically more viable to transport by truck. As for most shipments transport by truck is selected to minimize the total costs, the model becomes more sensitive to the fixed costs for trucks compared to the fixed costs for trains. For the variable transport cost terms it can be seen that the model is most sensitive to a change in the variable transport costs of trucks. A reduction of 50% in the variable costs would decrease the total costs with 12.9%. From the different vessel types, the model is most sensitive to the variable transport costs of M6 vessels. A change of 50% of this parameter would change the total costs with 5.2%. The model is relatively unsensitive to a change in hub establishment costs. For this specific model sensitivity test, it is allowed to establish new hubs to minimize costs. This means that the total costs changes a bit compared to the total costs as described in the base model as hub establishment costs are applied and cargo can be routed differently. To minimize total costs in the base model with hub establishment, the model selects to establish the hubs Rail terminal and Homberg 1 and the total costs of the base model with hub establishment are €989,411.18. A more in depth analysis and description of hub analysis will be provided in the next chapter. For the sensitivity test on hub establishment and terminal extension costs it has been chosen to change the establishment and extension costs all at once. The reason for this is that an increase or decrease of, for instance, material cost would be the case for all terminals. By changing the hub establishment costs all at once, the model does not select different hub for establishment. The parameters as shown in Table 5 is the sum of the cost terms for both hubs.

The analysis shows that the model is relatively unsensitive to the transshipment costs. From the base model, it can be seen that the transshipment costs are only 2.3% of the total costs. Therefore, even a 50% change in transshipment costs, results in a maximum change in total costs of 0.9%.

The model is relatively sensitive to the capacity of trucks. A decrease in the capacity of trucks results in an increase in the total costs because more trucks are needed to transport the same amount of cargo. However, the model is more sensitive to a reduction of the truck capacity than to an increase in the capacity of trucks. Lastly, the sensitivity results of the loading rate of the crane shows that a reduction of 50% of the loading rate increases the total costs with 5.2%.

From the sensitivity analysis, it can be seen that the model shows low overall sensitivity to most parameter changes. Even with variations of 50% of parameters, the change in total costs is relatively small. The high total costs for transporting all shipments result in a relatively small proportional impact. This means that the cost output is relatively stable, which is valuable for strategic planning under uncertainty. The model seems to be most sensitive to the variable transport costs of trucks, the capacity of trucks, and the fixed vehicle costs of trucks. This indicates the dominant role of trucks in the network. Changes in truck-related costs affect the total costs more significantly. Therefore, these factors should be monitored closely. The sensitivity to the loading rate of cranes in the terminals has a noticeable impact on the total costs. This is specifically the case when the loading rate decreases. This indicates that the loading rate should be monitored closely and if possible, the handling in terminals should be optimized to at least maintain the loading rate level.

It should be noted that the sensitivity of the model goes in hand with the shipments as defined for the base model. The shipments do not change for the different scenarios in order to compare the results equally. However, changing the shipments as input for the model can result in different percentage change of the total cost.

Table 6.6: Sensitivity analysis with parameter values and percentage change of the total costs.

Parameter	Parameter values							Percentage changes (%)					
	-50%	-25%	-10%	Base	+10%	+25%	+50%	-50	-25	-10	+10	+25	+50
FC M2	1300.00	1950.00	2340.00	2600.00	2860.00	3250.00	3900.00	-1.15	-0.58	-0.23	0.23	0.58	1.15
FC M4	1587.50	2381.25	2857.50	3175.00	3492.50	3968.75	4762.50	-1.56	-0.78	-0.31	0.31	0.78	1.56
FC M6	4110.00	6165.00	7398.00	8220.00	9042.00	10275.00	12330.00	-2.83	-1.42	-0.57	0.57	1.42	2.83
FC M8	10900.00	16350.00	19620.00	21800.00	23980.00	27250.00	32700.00	-7.51	-3.75	-1.50	1.50	3.75	7.51
FC truck	87.26	130.89	157.07	174.52	191.97	218.15	261.78	-7.33	-3.67	-1.47	1.47	3.67	7.33
FC train	5788.50	8682.75	10419.30	11577.00	12734.70	14471.25	17365.50	-2.85	-1.42	-0.57	0.57	1.31	2.26
C M2	0.046	0.069	0.083	0.092	0.101	0.115	0.138	-4.50	-2.15	-0.84	0.84	1.76	2.26
C M4	0.032	0.048	0.058	0.064	0.070	0.080	0.096	-4.16	-1.91	-0.72	0.72	1.92	3.63
C M6	0.018	0.027	0.032	0.036	0.040	0.045	0.054	-5.21	-2.60	-1.16	1.16	2.61	5.18
C M8	0.013	0.019	0.023	0.025	0.028	0.031	0.038	-1.36	-0.68	-0.23	0.34	0.68	1.48
C truck	0.063	0.094	0.113	0.125	0.138	0.156	0.188	-12.91	-4.68	-1.39	1.51	3.60	7.17
C train	0.023	0.034	0.041	0.045	0.050	0.056	0.068	-2.56	-1.28	-0.47	0.58	1.27	2.46
CE t	2091.00	3136.50	3763.80	4182.00	4600.20	5227.50	6273.00	-0.21	-0.11	-0.04	0.04	0.11	0.21
CT M2	20.65	30.98	37.17	41.30	45.43	51.63	61.95	-0.10	-0.05	-0.02	0.02	0.05	0.10
CT M4	27.38	41.06	49.28	54.75	60.23	68.44	82.13	-0.13	-0.07	-0.03	0.03	0.07	0.13
CT M6	34.10	51.14	61.37	68.19	75.01	85.24	102.29	-0.64	-0.32	-0.13	0.13	0.32	0.64
CT M8	52.62	78.92	94.71	105.23	115.75	131.54	157.85	-0.18	-0.09	-0.04	0.04	0.09	0.18
CT truck	21.73	32.59	39.11	43.45	47.80	54.31	65.18	-0.15	-0.07	-0.03	0.03	0.07	0.15
CT train	231.09	346.63	415.95	462.17	508.39	577.71	693.26	-0.92	-0.46	-0.18	0.18	0.46	0.92
Cap truck	9.0	13.4	16.1	17.9	19.7	22.4	26.9	14.41	4.81	1.58	-1.36	-2.92	-4.90
Cap train	195.0	292.5	351.0	390.0	429.0	487.5	585.0	3.71	1.56	0.25	-0.44	-1.08	-0.59
v load	235	352.5	423	470	517	587.5	705	5.21	2.06	1.01	0.06	-0.46	-1.09

7 Scenario-based analysis

In order to find answers on the sub-question *"How does establishment of strategic modal shift locations affect the shipping costs and CO_2-equivalent emissions of the transport in response to lowering river discharge levels?"* different scenarios have to be defined. The scenarios are based on lowering river discharge levels and changes in the available railway capacity. The model initially assumed that trains are unlimited available in the terminals. This can result in a strong increase in the market share of rail freight transport, while the capacity is not available in reality. Therefore, the capacity of rail freight transport is one of the factors used for building scenarios, as well as the river discharge levels.

The base model is based on a river discharge of 1400 m^3/s, which is the normal river discharge at Lobith. The current Agreed Low River discharge is 1020 m^3/s. The future Agreed Low River discharges are expected to decrease in the future. Therefore, expected Agreed Low River discharges of 2050 and 2085-2100 will also be used for the scenarios. The Agreed Low River discharge of 2050 is expected to be 800 m^3/s (Van der Mark, 2022). The Agreed Low River discharge of 2085-2100 is expected to be 650 m^3/s.

The current rail capacity from Rotterdam to the German hinterland (in ton per day) is derived from the base model. In the base model, at normal river discharge, the total transported cargo by train was 1767.0 ton. Therefore, if the capacity of rail freight transport does not change in the future, the capacity equals 1767.0 ton per day. It is also possible that the rail freight capacity decreases. This could have different causes. The political environment is uncertain. The sector would like to see investments to increase the capacity of the rail infrastructure (van Infrastructuur en Waterstaat, 2023). Infrastructure investments require long-term planning strategies and changing political environments can prioritize budgets differently. It can also be that, with shifting visions of European policy makers, the priority for passenger rail transport increases. This would limit the available slots for freight trains, which decreases the daily rail freight capacity. Climate-related disruptions, such as heat stress can also decrease the available daily capacity of rail freight transport. The decrease in available rail capacity is assumed to be 15%. This results in a daily rail capacity of 1502.0 tons.

Given the goal of the European Green Deal to shift 75% of the road freight transport to more sustainable transport modalities, future decrease of rail freight transport capacity is not very likely. It is also possible that rail freight capacity increases. This can be a result of public investments in rail infrastructure with increased prioritization of freight corridors to contribute to drought resilient freight corridors. Another reason for increase in rail transport capacity can be the adoption of the rail network to longer and heavier freight trains or further digitization which enables denser scheduling. In 2050, the rail freight capacity can be increased by 25% (van Infrastructuur en Waterstaat, 2023). The available rail capacity would then become 2209 tons.

The varying water levels can be combined with different rail freight capacity levels to the scenarios as shown in Table 7.1. For scenario *Current ALR* it is chosen not to vary the available rail freight capacity, because expansion of the rail freight network takes years. Expansion of the rail capacity is not an objective in this research, but the impact of this can be analyzed in the scenarios with future river discharge levels. For all scenarios, it is relevant to investigate the results without allowing for hub establishment and terminal extension and with allowing for hub establishment and terminal extension. This creates two cases for each scenario which can be compared against each other to gain insights in the impact of hub establishment in different future scenarios.

Table 7.1: Overview of the scenarios with the corresponding water discharge level and the rail freight capacity.

Scenario	Name	Water discharge level	Rail freight capacity	Establishment or extension
1	*Current ALR*	1020	Normal	Allowed
2	*Regression*	800	Low	Allowed
3	*Stagnation*	800	Normal	Allowed
4	*Adaptation*	800	High	Allowed
5	*Crisis*	650	Low	Allowed
6	*Disruption*	650	Normal	Allowed
7	*Maximizing sustainable shift*	650	High	Allowed

For each scenario, results will be provided on the cost specification for transporting all shipments to their destinations, the terminal utilization will be described and based on the transport performance, the total CO_2-equivalent emissions of the transport will be provided. The results from different scenarios will be compared against each other to analyze the impact of lowering water levels, the impact of hub establishment and the impact of variations in the available rail capacity.

Lowering river discharge scenarios affects the available draught in each scenario. Table 7.2 shows the available draught for the different river discharge levels and Figure 7.1 visualizes the available draughts in the different river sections for the different river discharge levels.

Table 7.2: Overview of the available draught on different sections of the river in different scenarios of river discharge. The gauge stations represent the sections. From Rotterdam to Druten, from Druten to Lobith, and so on.

Gauge station	Available draught Q = 1400	Available draught Q = 1020	Available draught Q = 800	Available draught Q = 650
Druten	431	352	307	276
Lobith	540	459	412	380
Duisburg	327	253	209	180
Köln	289	213	169	139
Kaub	231	152	107	76
Maxau	264	155	115	91
Basel	321	260	225	201

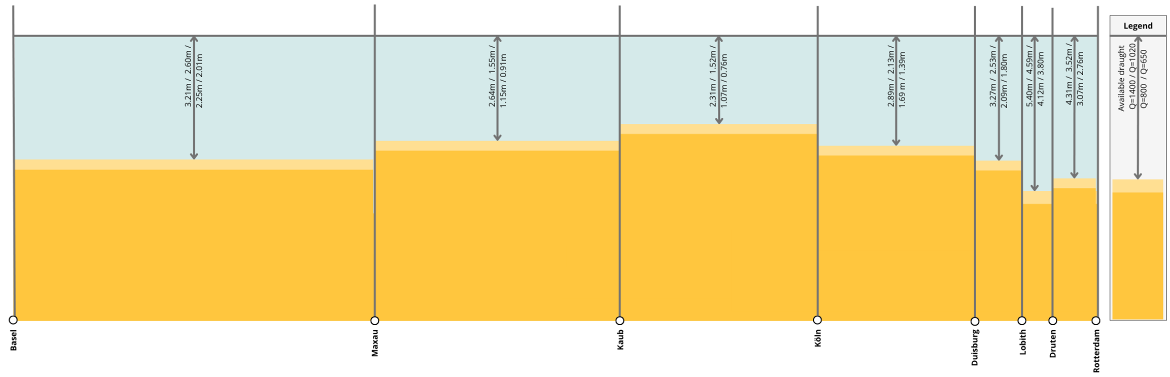


Figure 7.1: Available draught of the river sections from Rotterdam (right) to Basel (left) when river discharge at Lobith is 1400, 1020, 800 and 650 m^3/s.

Scenarios 2, 3, and 4 have similar water discharge levels and scenarios 5, 6, and 7 have similar water discharge levels. However, for both sets, the available rail freight capacity varies. Therefore, it makes sense to compare the results of the scenario of the second set (scenarios 5, 6, and 7) to the scenario with the same available rail freight capacity level of the first set (scenarios 2, 3, and 4). This way, the impact of lowering water levels can be analyzed. Comparison of the results within this set show the impact of increasing available rail capacities. For each scenario, a case is analyzed based on the currently existing terminals only and a case is analyzed based on the currently existing terminals and the established new hubs is analyzed. This way, the impact of establishment of new hubs can be analyzed.

7.1. Design of the network

Before analyzing the establishment of new hubs and extension of existing terminals, the terminals and hubs selected by the model have to be analyzed first for the different river discharge scenarios. The design of the network is needed to analyze the results of the different scenarios because it is not realistic to invest in different hubs or terminals for different scenarios. Selection of the terminals to extend or the hubs to establish is necessary for investigating the climate resilience of the network.

The establishment of new hubs and the extension of existing terminals must be beneficial for future low river discharge levels. Table 7.3 shows which new hubs or extended terminals are selected in the scenarios with future river discharge levels. From the selected hubs and terminals, it can be seen that only new hubs are selected. In terms of cost minimization, the model does not select to extend existing terminals. This indicates that the capacities of the existing terminals does not limit the amount of cargo that should have been transshipped in a terminal to minimize the total costs in terms of low water levels. This shows, however, that the location of transshipment in a hub with in some cases accessibility to rail, can be optimized to minimize the total costs. It can be seen that in each scenario the same three hubs are selected for establishment to minimize the total cost: River Harbour, the Rail terminal and Homberg 1 (which is the smallest option of Homberg included in this research). It can also be seen that, although the Rail terminal also has access to road infrastructure, the terminal is only selected for transshipments to rail transport. This results in a maximum capacity utilization of the hub of only 9.6%. However, it is the only terminal in the region that would allow for transport by rail. Therefore, it is useful to analyze the impact of the establishment of the Rail terminal. From Table 7.3 it can also be seen that Homberg 1 has the highest capacity utilization. The terminal capacity of the Rail terminal would be twice the size of the capacity of Homberg 1. Therefore, it shows lower capacity utilization for the Rail terminal.

Table 7.3: Hub and extended terminal selection in each scenario with future river discharge levels including the terminal market share for rail and the capacity utilization of the selected hubs/terminals.

Scenario	Selected hub/terminal	Terminal market share rail	Capacity utilization
Regression	River Harbour	0%	7.0%
	Rail terminal	100 %	6.7%
	Homberg 1	0%	85.5%
Stagnation	River Harbour	0%	7.0%
	Rail terminal	100 %	7.8%
	Homberg 1	0%	84.9%
Adaptation	River Harbour	0%	7.0%
	Rail terminal	100 %	9.6%
	Homberg 1	0%	82.9%
Crisis	River Harbour	0%	16.6%
	Rail terminal	100 %	6.7%
	Homberg 1	0%	59.3%
Disruption	River Harbour	0%	16.6%
	Rail terminal	100 %	7.8%
	Homberg 1	0%	57.3%
Maximum utilization	River Harbour	0%	15.5%
	Rail terminal	100 %	9.6%
	Homberg 1	0%	54.9%

In scenario *Adaptation* it is important to notice that all transshipments to rail are done in the Rail terminal. In all other terminals and selected hubs, cargo shifts to road transport. The cargo that shifts to rail in the Rail terminal is below the available rail capacity. 97.6% of the rail capacity would be used in this case. In scenario *Maximum utilization*, from all selected terminals, cargo only shifts to rail in the Rail terminal. Here 98.0% of the available rail capacity would be used. In all other scenarios, the full capacity of rail transport has been used in order to minimize costs for transporting all shipments through the network.

The minimization of total costs consists of the fixed and variable costs for transport, transshipment, and hub establishment costs. It can be useful to include a budget for the daily hub establishment and terminal selection costs. However, it is very hard to quantify this budget and since the same three hubs are selected for cost minimization, it makes more sense to analyze the hub selection when it is only allowed to establish 2. When allowing only for establishment of 2 hubs, River Harbour is not selected in all scenarios, and the cargo that would have been handled in this hub shifts to other, already existing terminals. This results in a total cost increase of 8.5% in the future scenarios. The total establishment cost of the selected hubs is €4,182.00. If a budget of, for instance, €4,000.00 would be considered, River Harbour and Homberg 1 would be selected. Including a budget of €4,000.00 results in a total cost increase of 2.2%.

Allowing for all hubs to be esatblished for the *Current ALR*, the Rail terminal and Homberg 1 are the only two terminals selected for total cost minimization. Given the relatively low terminal capacity utilization of River Harbour in all future scenarios and the fact that transshipments only shift to road here, it was chosen not to include River Harbour in the final design to compensate for not including a budget for hub establishment. Based on the results as described in this section, the scenarios will be based on a network where, if hubs are allowed to be established, the Rail terminal and Homberg 1 will be established.

7.2. Scenario 1: Current ALR

In this scenario, the river discharge is 1020 m^3/s and the capacity of the rail freight network is normal, which means that the capacity for transporting cargo to rail transport equals the amount of cargo shifted to rail in the base model. Because establishment of new hubs can be finished before 2050 (the next expected low river discharges), it is relevant to analyze already how establishment of the hubs affect the system at the current Agreed Low River discharge level. Therefore, two cases are analyzed in this scenario: one where hub establishment is not allowed and one where it is allowed.

7.2.1. Without hub establishment

For this case, the cost breakdown can be seen in Table 7.4. In this case, no hubs have yet been selected and no terminals have been extended. 1020 m^3/s is the current Agreed Low River discharge level. Hub establishment and terminal expansion can take multiple years considering licensing procedures.

From Table 7.4 it can be seen that the total cost for transporting all shipments from Rotterdam to the destination is over 1.05 million euros. 53.7% of the cost are the variable costs for transport, 44.0% of the total cost are fixed vehicle costs and the remaining costs are transshipment costs.

Table 7.4: Cost breakdown of the scenario *Current ALR* where river discharge is 1020 m^3/s and the rail capacity level is normal.

Total cost	**€1,052,128.94**
Fixed vehicle cost	€462,906.84
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€197,616.84
Transport cost	€565,505.29
Total transfer cost	€23,716.81
Hub establishment cost	€0.00

Comparing the costs of *Current ALR* to the costs of the base model, it can be seen that the lowering river discharge from 1400 to 1020 m^3/s results in an increase of 3.0% of the total costs. The fixed vehicle costs decreased 4.5% because of different usage of trucks and trains. However, as a result of that the variable transport costs increased with 7.5%. The transfer costs slightly changed with an increase of 3.3%. These changes resulted in the overall increase of costs when river discharge decreases from 1400 to 1020 m^3/s.

Table 7.5 shows the utilization of terminals that are selected by the model for transshipment of the cargo to other modalities. It should be noted that the terminal utilization is based on a terminal capacity of only 54% of the total terminal capacity to correct for only including port-hinterland transport. It shows that only a small part of the capacity of CTU Tiel is used (1.4%), while the full capacity allocated to port-hinterland transport of Nordfrost Wesel is used for transshipments. 1,538.0 ton is shifted to continue transport by rail in Contargo Emmerich. This equals 9.2% of the transported cargo. The rail capacity utilization equals 87.0% All other cargo continues by road transport.

Table 7.5: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and to rail specified for each terminal.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
CTU Tiel	85.8 ton	1.4%	85.8 ton	-
BCTN Nijmegen	3,891.5 ton	32.0%	3,891.5 ton	-
Contargo Emmerich	1,538.0 ton	12.6%	-	1,538.0 ton
Nordfrost Wesel	6,088.5 ton	100.0%	6,088.5 ton	-
UCT Dormagen	2,567.1 ton	42.2%	2,567.1 ton	-
Contargo Ginsheim	2,588.1 ton	42.5%	2,588.1 ton	-

Table 7.6 shows the transport performance of each transport modality and the total emissions for transporting the shipments from Rotterdam to the right final destination. It can be seen that the transport performance for M2 vessels is smallest, while the transport performance of M6 vessels is the highest indicating that more cargo is transported over longer distances. The transport performance of trucks is higher compared to the transport performance of trains. This also indicates that more cargo is transported over longer distances. Although cargo that is transported by train generally exceeds a certain distance threshold, the capacity of the rail network limits the maximum transport performance of trains. The model aims to minimize the total costs by prioritizing certain shipments for transport

from a terminal to the destination if the flow and distance are great enough. It can be seen that the total emissions for transport equal about 313.000 kilograms of CO_2-equivalent units.

Table 7.6: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	**Transport Performance [ton-km]**
M2	803,484.46
M4	1,129,608.22
M6	2,553,131.29
M8	1,127,408.75
Truck	1,858,928.67
Train	1,012,577.39
CO_2-eq emission	312,923.25

Comparing this scenario to the base model, it can be seen that a reduction in the river discharge results in an increase of the total costs because of different usage of trucks and trains. With the smaller available draughts, some cargo from certain shipments has to be unloaded of the vessel to comply with the available draught on a next section of the river. The different usage of transport modalities and vehicles in the routing of the shipments also increases the CO_2-equivalent emissions of the transport.

7.2.2. With hub establishment

To analyze the impact of hub establishment in the *Current ALR* scenario, it is now allowed to use established hubs. Table 7.7 shows the total cost and a specification of each component of the total cost when the established hubs can be used for the current Agreed Low River discharge level. It shows that the total costs are about 1.019 million euros. From this cost, 46.3% are fixed vehicle costs, 50.7% are variable transport costs, 2.5% are transfer cost and the remainder of 0.5% are hub establishment costs. Comparing the total costs to the case without hub establishment, it can be seen that the costs have decreased with 3.1%. Although the fixed vehicle costs have increased with 2.0% as a result of the Rail terminal near Nijmegen, the variable costs for transport have decreased with 8.5%. This is a first indication that establishment of hubs changes the transport routing and transshipment decisions in a way that reduces the total costs.

Table 7.7: Cost breakdown of the scenario *Current ALR* where river discharge is 1020 m^3/s and the rail capacity level is normal. It is allowed to use the established new hubs.

Total cost	**€1,019,766.53**
Fixed vehicle cost	€472,389.60
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€207,099.60
Transport cost	€517,401.74
Total transfer cost	€25,793.19
Hub establishment cost	€4,182

Table 7.8 gives an overview of the transshipments in the terminals and the corresponding terminal utilization. It can be seen that in the Rail terminal, the full available capacity for rail transport is used. Most of the cargo (62.2%) is transshipped in the hub Homberg 1. Part of the cargo is further transported by waterborne transport to UCT Dormagen and Contargo Ginsheim. Comparing these results with the results of this scenario without establishment of new hubs, it can be seen that the cargo that continues all the way to UCT Dormagen and Contargo Ginsheim, reduces by 32.5 and 0.4% respectively as a result of hub establishment. It also shows that the utilization of terminal capacity of BCTN Nijmegen allocated to port-hinterland transport decreases with establishment of hubs. However, with the Rail terminal

near Nijmegen, the available rail capacity is fully utilized. This is a first indication of the value of having a terminal with access to rail infrastructure around Nijmegen from a cost minimization perspective.

Table 7.8: Terminals and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and to rail specified for each terminal/hub.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
BCTN Nijmegen	253.0 ton	2.1%	253.0 ton	-
Rail terminal	1,767.0 ton	7.8%	-	1,767.0 ton
Homberg 1	10,427.3 ton	92.5%	10,427.0 ton	-
UCT Dormagen	1,734.0 ton	28.5%	1,734.0 ton	-
Contargo Ginsheim	2,577.7 ton	42.3%	1,734.0 ton	-

Table 7.9 shows the transport performance of each transport modality and the total emissions for transporting the shipments from Rotterdam to the right final destination. It can be seen that the transport performances of the vessels of all types are relatively high compared to the performances of trains and trucks. Comparing these transport performances to the case without hub establishment, it can be seen that by establishment of hubs, the transport performance of all vessel types and trains increase while the transport performance of trucks decreases. Along with reduction of the total costs, the total CO_2-equivalent emissions of the transport reduces with 24.5%. This is a first indication that shows that establishment of transport hubs contributes to increasing the market share of waterborne transport.

Table 7.9: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	902,563.76
M4	1,299,395.86
M6	2,617,049.27
M8	1,247,790.54
Truck	1,139,467.99
Train	1,264,816.56
CO_2-eq emission	251,423.56

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.1% and the CO_2-equivalent emissions of the transport with 24.5%. From the transport performances it can be seen that establishment of hubs increases all transport performances, except for the transport performance of trucks which decreases. This is a first indication that, from a cost minimization perspective, transport hubs contribute to increasing the market share of waterborne transport, even for the current Agreed Low River discharge level and based on the current available rail infrastructure.

7.3. Scenario 2: Regression

In this scenario, the river discharge is 800 m^3/s and the capacity of the rail freight network is low, which means that the capacity for transporting cargo to rail transport equals only 85% of the amount of cargo shifted to rail in the base model. In this scenario, two cases are analyzed: one where hub establishment is not allowed and one where it is allowed.

7.3.1. Without hub establishment

Table 7.10 shows an overview of the costs. Here it can be seen that the total costs to transport all shipments from Rotterdam to its final destination is about 1.113 million euros. It can be seen that, compared to the scenario *Current ALR*, the total costs are higher which is mainly caused by an increase in the variable transport costs and the total transfer costs. The results show that in this scenario without hub establishment, the transport costs equal 56.5%, the fixed vehicle costs equal 41.2% and rest is for transshipment.

Table 7.10: Cost breakdown of the scenario *Regression* where river discharge is 800 m^3/s and the rail capacity level is low.

Total cost	**€1,122,947.78**
Fixed vehicle cost	€463,225.88
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€197,965.88
Transport cost	€634,082.24
Total transfer cost	€25,609.65
Hub establishment cost	€0.00

Table 7.11 shows the terminals selected for transshipments to minimize the total costs. It can be seen that here again, the terminal capacity of Nordfrost Wesel allocated to port-hinterland transport is fully used for transshipments. It can also be seen that only small parts of the capacity of CTU Tiel, Contargo Emmerich and Rhein Ruhr Terminal Gateway are used. However, 754.2 ton is shifted to continue transport by rail in Contargo Emmerich and 747.8 ton is shifted to continue transport by rail in Rhein Ruhr Terminal Gateway. This equals 9.0% of the transported cargo. The rail capacity utilization equals 100%. All other cargo continues by road transport. So although little capacity of Contargo Emmerich and Rhein Ruhr Terminal Gateway are used, these terminals allow for transshipment to rail transport. Comparing the shifts in the terminals in this scenario with the shifts of *Current ALR*, it can be seen that less cargo is transported all the way to Contargo Ginsheim. This is a first indication that lowering river discharges decrease the distance that cargo can be transported by waterborne transport.

Table 7.11: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and to rail specified for each terminal.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
CTU Tiel	479.6 ton	7.9%	479.6 ton	-
BCTN Nijmegen	5,463.0 ton	44.9%	5,463.0 ton	-
Contargo Emmerich	754.2 ton	6.2%	-	754.2 ton
Nordfrost Wesel	6,086.0 ton	100.0%	6,086.0 ton	-
Rhein Ruhr Terminal (Gateway)	747.8 ton	2.1%	-	747.8 ton
UCT Dormagen	2,930.7 ton	48.1%	2,930.7 ton	-
Contargo Ginsheim	297.7 ton	4.9%	297.7 ton	-

Table 7.12 shows the transport performance of each transport modality and the CO_2-equivalent emissions of the transport. It can be seen that the transport performance for M2 and M8 vessels is much smaller than the transport performance of M4 and M6 vessels. It can also be seen that the transport performance of trains is much smaller than the transport performance of rail. This can be a result of the limited capacity of the rail freight network. Less cargo can be transported by rail, while the distances do not increase. This results in a decrease in the transport performance. At the same time, the remaining cargo has to be transported to the final destination which results in an increase of the transport performance of trucks. If we compare this with *Current ALR*, it can be seen that lowering river discharge and a decrease in transport capacity of the rail freight network results in a strong decrease of the transport performance of M2, M6 and M8 vessels. The transport performance of M4 vessels increases slightly. The transport performance of trains decreases while the transport performance of trucks strongly increases.

Table 7.12: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	578,237.2
M4	1,163,149.7
M6	1,930,329.9
M8	978,382.3
Truck	2,857,855.7
Train	864,377.9
CO_2-eq emission	395,508.40

Comparing these results to the results of *Current ALR*, it can be seen that lowering water levels in combination with lower available rail capacity increases the total costs with 6.7%. Although the total fixed vehicle costs does not change much, an increase of 12.1% of the variable transport costs can be identified. From the transport performances it can be seen that the performance for all vessel types except for M4 vessels decreases, as well as the transport performance of trains. The transport performance of trains decreases because less cargo is being transported by train. This simultaneously results in an increase of the transport performance of trucks. The CO_2-equivalent emissions increase with 26.4%.

7.3.2. With hub establishment

To analyze the impact of hub establishment in the *Regression* scenario, it is now allowed to use the established hubs. Table 7.13 shows the cost breakdown when the established hubs can be used for transshipment in order to minimize the total costs. It can be seen that the total costs are over 1.087 million euros, which is less than the same scenario without using the established hubs. The total costs decrease with 26,000 euros, which equals 3.2% cost reduction of shipments of one day. From the cost breakdown it can be seen that the fixed vehicle costs and the transfer costs are about equal, but a reduction of the total cost is caused by a reduction in the variable transport costs. To explain this, the terminal utilization for transshipments and the transport performance have to be analyzed first.

Table 7.13: Cost breakdown of the scenario *Regression* where river discharge is 800 m^3/s and the rail capacity is low. It is allowed to use the established new hubs.

Total cost	**€1,087,096.19**
Fixed vehicle cost	€463,081.36
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€197.791.36
Transport cost	€595,724.11
Total transfer cost	€24,108.71
Hub establishment cost	€4,182.00

Table 7.14 shows the utilization of the terminals and hubs selected to transship cargo. It should be noted that from analyzing the designs to minimize costs in different scenarios, the Rail terminal and Homberg 1 were selected. Therefore, in the case where established hubs can be used, only these two hubs can be used for transshipments. It can be seen that, with establishment of hubs, transshipments occurs in less terminals compared to when no hubs are established. If we compare the terminal utilization from Table 7.14 with the terminal utilization from Table 7.11, it can be seen that less cargo is shifted in and downstream BCTN Nijmegen. Instead of splitting transshipments to rail over multiple terminals, the results show that with the Rail terminal, 1,502.0 ton is shifted to continue transport by rail in the Railway terminal. This equals 9.0% of the transported cargo. The rail capacity utilization equals 100%. All other cargo continues by road transport. It can also be seen that 57.5% of the cargo of all shipments

shifts in Homberg 1, which is one of the established hubs. The cargo being transported by waterborne transport to UCT Dormagen and Contargo Ginsheim remains about equal.

Table 7.14: Terminals and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal/hub.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
BCTN Nijmegen	2,256.6 ton	18.5%	2,256.6 ton	-
Rail terminal	1,502.0 ton	6.7%	-	1,502.0 ton
Homberg 1	9,641.6 ton	85.5%	9,641.6 ton	-
UCT Dormagen	3,075.7 ton	50.5%	3,075.7 ton	-
Contargo Ginsheim	283.1 ton	4.7%	283.1 ton	-

Table 7.15 shows the transport performances of the transport modalities in this scenario when established hubs can be used. Here it can be seen that the transport performance of all modalities are quite high. The transport performance of M2 vessels appears to be somewhat lower. However, comparing these transport performances to the transport performances of the same scenario without establishment of hubs, it can be seen that establishment of the hubs increases all transport performances except for trucks. This is preferable, because a decrease in transport performance by trucks indicate that less goods are transported over shorter distances by truck. This explains the reduction in variable transport costs, because the variable costs per ton-kilometer transport by truck are highest of all modalities included in the model. Besides contributing to total cost reduction, the changes in transport performances compared to when hubs are not established contribute to CO_2-equivalent emission reduction. The emissions in this case are 338 thousand kilograms which is a reduction of 14.4% compared to the same scenario without hub establishment.

Table 7.15: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	771,296.1
M4	1,316,406.0
M6	2,017,944.0
M8	1,055,830.5
Truck	2,178,351.7
Train	1,067,735.8
CO_2-eq emission	338,464.2

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.2%. From the transport performances it could be seen that the transport performance of vessels increases with establishment of hubs. This simultaneously reduces the transport performance of trucks which means that less cargo has to be transported over shorter distances by trucks compared to when no hubs are established.

7.4. Scenario 3: Stagnation

In this scenario, the river discharge is 800 m^3/s and the capacity of the rail freight network is normal, which means that the capacity for transporting cargo by rail transport equals the amount of cargo shifted to rail in the base model at normal river discharge. In this scenario, two cases are analyzed: one where hub establishment is not allowed and one where it is allowed.

7.4.1. Without hub establishment

Table 7.16 shows an overview of the costs. It can be seen that the costs are about equal to the scenario *Regression* where the river discharge level is similar, but the rail freight capacity of the network is smaller. Because more cargo can be transported by train, the fixed and variable costs for transport and the transfer cost change a bit. The difference in rail capacity causes a decrease of 0.1% of the total costs when comparing the costs to scenario *Regression*.

Table 7.16: Cost breakdown of the scenario *Stagnation* where river discharge is 800 m^3/s and the rail capacity level is normal.

Total cost	**€1,121,582.90**
Fixed vehicle cost	€462,906.84
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€197,616.84
Transport cost	€633,104.81
Total transfer cost	€25,571.25
Hub establishment cost	€0.00

Table 7.17 shows the terminals selected for transshipment of cargo based on the currently existing terminals only. It can be seen that multiple terminals along the Rhine river are used for transshipment of the cargo. The terminal capacity allocated to port-hinterland transport of Nordfrost Wesel is fully used, while only a small part of the terminal capacity of CTU Tiel, Contargo Emmerich, Rhein Ruhr Terminal Gateway and Contargo Ginsheim are used. 758.0 ton is shifted to continue transport by rail in Contargo Emmerich and 780.0 ton is shifted to continue transport by rail in Rhein Ruhr Terminal Gateway. This equals 9.2% of the transported cargo. The rail capacity utilization equals 87.0%. All other cargo continues by road transport. Only 87% of the rail capacity is being used to transport the cargo. This can be a result of that the free capacity is too low to use an additional train. Because the capacity is measured in tons, the available capacity is a bit more than half a train. However, because additional fixed costs would be applied if the available capacity would have been used, the distance threshold increases significantly. Using the spare capacity is not economically viable. Therefore, not all capacity of the rail freight network is used to transport the cargo while minimizing costs.

Table 7.17: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
CTU Tiel	475.8 ton	7.8%	475.8 ton	-
BCTN Nijmegen	5,463.0 ton	44.9%	5,463 ton	-
Contargo Emmerich	758.0 ton	7.8%	-	758.0 ton
Nordfrost Wesel	6,086.0 ton	100%	6,086.0 ton	-
Rhein Ruhr Terminal Gateway	780.0 ton	2.1%	-	780.0 ton
UCT Dormagen	2,905.8 ton	47.7%	2,905.8 ton	-
Contargo Ginsheim	290.4 ton	4.8%	290.4 ton	-

Table 7.18 shows the transport performances of the *Stagnation* scenario when no hubs are established. If we compare the transport performances of each transport modality to the transport performances of the scenario *Regression* when no hubs are established, it can be seen that the results are strongly comparable. The normal transport capacity level of the rail transport system results in a bit higher transport performance of trains and lower transport performance of trucks. However, the difference in transport performance is small. The CO_2-equivalent emissions of the transport in this scenario are 394 thousand kilograms, which is a decrease of only 0.3% compared to the scenario *Regression*.

Table 7.18: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	578,237.2
M4	1,163,498.6
M6	1,926,170.4
M8	978,382.3
Truck	2,845,483.2
Train	880,095,96
CO_2-eq emission	394,470.3

Comparing these results to the results of *Current ALR*, it can be seen that lowering water levels increases the total costs with 6.6% if the rail capacity does not change. Although the total fixed vehicle costs does not change much, an increase of 11.9% of the variable transport costs can be identified. From the transport performances it can be seen that the performance for all vessel types except for M4 vessels decreases, as well as the transport performance of trains. The transport performance of trains decreases because less cargo is being transported by train. This simultaneously results in an increase of the transport performance of trucks. This also increases the CO_2-equivalent emissions of the transport with 26.1%

7.4.2. With hub establishment

To analyze the impact of hub establishment in the *Stagnation* scenario, it is now allowed to use the established hubs. Table 7.19 shows the cost breakdown when the established hubs can be used for transshipment in order to minimize the total cost. It can be seen that the total costs are about 1,081 million euros. The variable transport costs equal 53.7%, the fixed vehicle costs equal 43.7%, the transfer costs equal 2.2% and the remainder is for hub establishment. Comparing the total costs of this scenario when hubs are established compared to the total costs when hubs are not established, it can be seen that the total costs reduce with 40,000 euros or 3.6%. While the fixed vehicle costs increase and hub establishment costs are applied, transport costs strongly decrease. It can be seen that also in this scenario, establishment of hubs results in overall cost reduction.

Table 7.19: Cost breakdown of the scenario *Stagnation* where river discharge is 800 m^3/s and the rail capacity level is normal. It is allowed to use the established new hubs.

Total cost	**€1,081,424.74**
Fixed vehicle cost	€472,215.08
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€206,925.08
Transport cost	€580,918.95
Total transfer cost	€24,108.71
Hub establishment cost	€4,182.00

Table 7.20 shows the utilization of the terminals and hubs selected for transshipments, and the shift to road and rail in each terminal. It can be seen that 1767.0 ton is shifted to continue transport by rail in the Rail terminal. This equals 10.5% of the transported cargo. The rail capacity utilization equals 100%. All other cargo continues by road transport. Furthermore, it can be seen that more cargo is being transshipped in Rail terminal and Homberg 1 compared to scenario *Regression*. This can be a result because more cargo can be transshipped in the Rail terminal, which allows some vessels to sail further to Homberg 1 for transshipment to transport by truck or train.

Table 7.20: Terminals and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal/hub.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
BCTN Nijmegen	2,221.8 ton	18.2%	2,221.8 ton	-
Rail terminal	1,767.0 ton	7.8%	-	1,767.0 ton
Homberg 1	9,572.5 ton	84.9%	9,572.5 ton	-
UCT Dormagen	2,914.6 ton	47.9%	2,914.6 ton	-
Contargo Ginsheim	283.1 ton	4.6%	283.1 ton	-

Table 7.21 shows the transport performance of each transport modality and the CO_2-equivalent emissions of the transport. It can be seen that the transport performances of the larger vessel types (M4, M6, and M8) and truck and train are again quite high. Comparing these transport performances to the transport performances of the transport modalities in the same scenario without establishment of hubs, it can be seen that the transport performances of all transport modalities are higher, except for the transport performance of trucks. For this scenario it can be seen that establishment of hubs allows for transporting more cargo over greater distances by all modalities except for trucks, where the transport performance decreases. The total CO_2-equivalent emission of the transport is 324,7 thousand kilograms, which is a reduction of 17.7% compared to when no hubs are established.

Table 7.21: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	769,863.8
M4	1,264,521.7
M6	2,017,944.0
M8	1,055,830.5
Truck	2,016,965.2
Train	1,264,816.5
CO_2-eq emission	324,761.4

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.6%. From the transport performances it could be seen that the transport performance of vessels increases with establishment of hubs. This simultaneously increases the transport performance of rail and reduces the transport performance of trucks which means that less cargo has to be transported over shorter distances by trucks compared to when no hubs are established. This also results in a reduction of CO_2-equivalent emissions of 17.7%.

7.5. Scenario 4: Adaptation

In this scenario, the river discharge is 800 m^3/s and the capacity of the rail freight network is high, which means that the capacity for transporting cargo to rail transport is increased with 25% of the amount of the cargo shifted to rail in the base model at normal river discharge. In this scenario, two cases are analyzed: one where hub establishment is not allowed and one where it is allowed.

7.5.1. Without hub establishment

Table 7.22 shows the cost breakdown of the scenario *Adaptation* without allowing for establishment of hubs. Here it can be seen that the total costs equal 1,117 million euros. Compared to scenario *Stagnation*, the total costs are reduced with 0.4%. The fixed vehicle costs are 470 thousand euros, which is higher than the fixed vehicle costs in scenario *Stagnation* without establishment of new hubs. This can be a result of adding more trains to transport cargo. The rail capacity is increased and adding another train would add additional fixed costs to the total cost. The transport costs of 621 thousand euros are decreased compared to the transport costs in scenario *Stagnation*. The transfer costs are, with about 25,200 euros, also somewhat smaller compared to scenario *Stagnation*. This results in a small decrease in overall total costs.

Table 7.22: Cost breakdown of the scenario *Adaptation* where river discharge is 800 m^3/s and the rail capacity level is high.

Total cost	**€1,117,383.99**
Fixed vehicle cost	€470,644.39
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€205,354.39
Transport cost	€621,539.57
Total transfer cost	€25,199.02
Hub establishment cost	€0.00

Table 7.23 gives an overview of the terminals selected for transshipment of cargo. It shows the terminals that are used for transshipments. It can be seen that, in terms of cost minimization, in all scenarios with a river discharge of 800 m^3/s where establishment of hubs is not allowed, the same terminals are being used. However, now with increased capacity for rail transport, 758.0 ton is shifted to continue transport by rail in Contargo Emmerich and 1,170.0 ton is shifted to continue transport by rail in Rhein Ruhr Terminal Gateway. This equals 11.5% of the transported cargo. The rail capacity utilization equals 87.3%. All other cargo continues by road transport. The rail capacity utilization of 87.3% indicated that not all capacity of rail is being used. In terms of cost minimization, it is probably more economically viable to transport part of the cargo by truck instead of adding an additional train. If the train is not filled up to the full capacity - which is a result of measuring the rail capacity based on shifted cargo and percentage change - it has to transport cargo over a much greater distance to be economically viable. Comparing the transshipments in the terminals of this scenario with scenario *Stagnation* without establishment of hubs, it can be seen that the terminal utilization remain about equal, but small shifts occur to shift more cargo to rail transport in Rhein Ruhr Terminal Gateway.

Table 7.23: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
CTU Tiel	475.8 ton	7.8%	475.8 ton	-
BCTN Nijmegen	5,419.0 ton	44.5%	5,419.0 ton	-
Contargo Emmerich	758.0 ton	6.2%	-	758.0 ton
Nordfrost Wesel	6,086.0 ton	100%	6,086.0 ton	-
Rhein Ruhr Terminal	1,170.0 ton	3.2%	-	1,170.0 ton
UCT Dormagen	2,559.8 ton	42.0%	2,559.8 ton	-
Contargo Ginsheim	290.4 ton	4.8%	290.4 ton	-

Table 7.24 shows the transport performance of each transport modality in this scenario and the corresponding total CO_2-equivalent emissions for the transport. It can be seen that the transport performances of M2 and M8 vessels are now below 1 million ton-kilometer and that the total CO_2-equivalent emissions for transport are about 382.4 thousand kilograms. Comparing these with *Stagnation*, it can be seen that the transport performances for M2, M4, and M8 vessels remain unchanged. The transport performance of M6 vessels slightly decreases, which can be a result of cargo being transshipped from M6 vessels to other modalities more downstream because the rail capacity is larger in this scenario. The transport performance of truck decreases, while the transport performance of trains increases. The total emissions for the transport decrease with 3%.

Table 7.24: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	578,237.2
M4	1,163,498.6
M6	1,908,580.6
M8	978,382.3
Truck	2,702,094.1
Train	1,035,959.6
CO_2-eq emission	382,436.6

Comparing these results to the results of *Current ALR*, it can be seen that lowering water levels increases the total costs with 6.2% if the rail capacity increases with 25%. Although the total fixed vehicle costs does not change much (+1.7%), an increase of 9.9% of the variable transport costs can be identified. From the transport performances it can be seen that the performance for all vessel types except for M4 vessels decreases. The transport performance of trains slightly increases. This simultaneously results in an increase of 45.4% of the transport performance of trucks. This also increases the CO_2-equivalent emissions of the transport with 22.2%.

7.5.2. With hub establishment

To analyze the impact of hub establishment in the *Adaptation* scenario, it is now allowed to use the established hubs. Table 7.25 provides a specification on the costs for transporting all shipments from Rotterdam to its final destination. It shows that, in terms of cost minimization, with establishment of new hubs the total costs equal 1.077 million euros. 52.8% of the cost are variable transport costs. 44.6% of the costs are fixed vehicle costs. 2.3% are transfer costs and the remainder are hub establishment costs. As the hubs to be established are defined in section 7.1, the costs for hub establishment are equal in all cases where hubs can be established. Comparing these costs with the costs of the case of this scenario without establishment of hubs, the total costs decrease with 30,000 euros which equals a reduction of 3.6%. The fixed vehicle costs increase with 2%, while the transport costs decrease with 8.5%. This results in an overall decrease of the costs.

Table 7.25: Cost breakdown of the scenario *Adaptation* where river discharge is 800 m^3/s and the rail capacity level is high. It is allowed to use established new hubs.

Total cost	**€1,077,162.07**
Fixed vehicle cost	€479,952.64
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€214,662.64
Transport cost	€568,918.72
Total transfer cost	€24,108.71
Hub establishment cost	€4,182.00

Table 7.26 provides an overview of the terminals and hubs selected for transshipments of cargo and the corresponding terminal utilization. For each terminal it shows the amount of cargo that shifts to road and to rail transport. From this table, it can be seen that only a small part of the capacity of the terminals CTU Tiel, Contargo Emmerich, Rhein Ruhr Terminal Gateway and Contargo Ginsheim is being used, while over 40% of the terminal capacity allocated to port-hinterland transport is being used of BCTN Nijmegen and UCT Dormagen and 100% of the capacity allocated to port-hinterland transport of Nordfrost Wesel is being used. For modality shift it can be seen that 2,157.0 ton is shifted to continue transport by rail in the Rail terminal. This equals 12.9% of the transported cargo. The rail capacity utilization equals 97.6%. All other cargo continues by road transport. Comparing the results of Table 7.26 to the results where hubs were not established, it can be seen that Homberg 1 handles

more cargo than Nordfrost Wesel did. Nordfrost Wesel is now not being used anymore, indicating a shift from cargo that used to be handled there to being handled in Homberg 1. The utilization of BCTN Nijmegen is much lower because the Rail terminal takes over a significant part of the cargo to shift to rail transport.

Table 7.26: Terminals and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
BCTN Nijmegen	2,221.8 ton	18.2%	2,221.8 ton	-
Rail terminal	2,157.0 ton	9.6%	-	2,157.0 ton
Homberg 1	9,346.5 ton	82.9%	9,346.5 ton	-
UCT Dormagen	2,750.6 ton	45.2%	2,750.6 ton	-
Contargo Ginsheim	283.1	4.6%	283.1 ton	-

Table 7.27 shows the transport performances of the transport modalities when hubs are being established. It can be seen that The transport performances of the M8 and M4 vessel are about equal, indicating that both vessel types transport on average the same amount of cargo over the same distance. Comparing the transport performances to the performances when hubs were not established, it can be seen that the transport performances of M2, M4, and M6 vessels increased while the performance of M8 vessels slightly decreased. The transport performance of trucks significantly decreased with about 31%, while the transport performance of trains increased with 42.8%. The CO_2-equivalent emissions of the transport decreased with 18.3% from 383 thousand kilograms to 312 thousand kilograms by establishment of hubs.

Table 7.27: Transport performance of each transport modality and the CO_2-equivalent emission of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	769,863.8
M4	1,264,521.7
M6	1,938,023.7
M8	1,055,830.5
Truck	1,868,176.9
Train	1,478,177.9
CO_2-eq emission	312,104.4

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.6%. From the transport performances it could be seen that the transport performance of all vessel types increases with establishment of hubs. This simultaneously increases the transport performance of rail and reduces the transport performance of trucks which means that less cargo has to be transported over shorter distances by trucks compared to when no hubs are established. This also results in a slight reduction of CO_2-equivalent emissions of 0.3%.

7.6. Scenario 5: Crisis

In this scenario, the river discharge is 650 m^3/s and the capacity of the rail freight network is low, which means that only 85% of the capacity in the base model is available of transport by rail. In this scenario, two cases are analyzed: one where hub establishment is not allowed and one where it is allowed.

7.6.1. Without hub establishment

Table 7.28 provides an overview of the total costs for transporting all shipments in this scenario. It shows that the total costs are 1,17 million euros, which is quite high compared to the costs of the scenarios so far. Compared to the scenario *Current ALR*, the total costs have increased with 11.3%. This can be explained because low water levels require changes in the cargo transported by waterborne transport. The vessels can carry less cargo to ensure that the vessel draught does not exceed the available draught, and near Kaub, none of the vessels can pass because the available draught is smaller than the empty draught of the vessels. Therefore, cargo has to shift more downstream already to land modalities. However, in this scenario, the rail capacity is smaller compared to the capacity in the base scenario. Therefore, more cargo has to be transported by truck. This increases the total costs which can be seen by an increase in the fixed vehicle costs, a strong increase in variable transport costs (20%) and an increase in total transfer costs.

Table 7.28: Cost breakdown of the scenario *Crisis* where river discharge is 650 m^3/s and the rail capacity level is low.

Total cost	**€1,171,155.51**
Fixed vehicle cost	€465,001.08
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€199,711.08
Transport cost	€680,494.32
Total transfer cost	€25,660.11
Hub establishment cost	€0.00

Table 7.29 gives an overview of the terminals selected for transshipments and the corresponding terminal utilization and information on shift to road and rail. It can be seen that the terminal utilization of BCTN Nijmegen is quite high. From the total transported cargo, already 47.9% shifts to road transport in this terminal. another 30.2% of the cargo shifts in Nordfrost Wesel to road transport. It can be seen that 546.0 ton is shifted to continue transport by rail in Contargo Emmerich and 780.0 ton is shifted to continue transport by rail in Rhein Ruhr Terminal Gateway. These shifts to rail transport equal 7.9% of the total transported cargo. The rail capacity utilization equals 88.3%. All other cargo continues by road transport. Comparing these terminal utilization and shifts to *Regression*, it can be seen that the pressure increases to terminals more downstream because cargo has to be shifted off the waterway before Kaub. It can also be seen that Contargo Ginsheim is not being used for transshipments because the vessels cannot pass Kaub given the available draught.

Table 7.29: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
CTU Tiel	862.7 ton	4.5%	862.7 ton	-
BCTN Nijmegen	7,867.5 ton	64.6%	7,867.5 ton	-
Contargo Emmerich	546.0 ton	4.5%	-	546.0 ton
Nordfrost Wesel	5,068.2 ton	83.2%	5,068.2 ton	-
Rhein Ruhr Terminal Gateway	780.0 ton	2.1%	-	780.0 ton
UCT Dormagen	1,634.0 ton	26.8%	1,634.0 ton	-

Table 7.30 shows the transport performances of the transport modalities and the total CO_2-equivalent emissions of the transport based on the transport performances. It shows that the ttransport performance of M2 and M8 vessels is much lower than the transport performance of M4 and mainly of M6 vessels. This indicates that on M4 and M6 vessels more cargo is transported over greater distances. It can also be seen that the transport performance of trucks is very high, especially compared to the transport performance of trains. Since the available train capacity is not fully used in this scenario, there is potential for increasing the amount of transport by train. The total CO_2-equivalent emissions of this scenario is 445 thousand kilograms. Comparing these transport performances to scenario *Regression*, it

can be seen that the performance of M2 vessels has increased, while the performance of M4, M6, and M8 vessels has decreased. The transport performance by truck increased with 20.8% while the transport performance of trains decreased with 16.6%. So, if future capacity for freight transport by rail decreases, extreme decrease of water levels result in more transport by truck and less transport by train compared to normal decrease of water levels.

Table 7.30: Transport performance of each transport modality and the CO_2-equivalent emissions of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	608,027.6
M4	1,071,642.5
M6	1,700,886.8
M8	735,696.0
Truck	3,451,243.1
Train	721,132.7
CO_2-eq emission	445,097.3

Comparing these results to the results of *Regression*, it can be seen that lowering water levels increases the total costs with 4.3% when the available rail capacity is low compared to the base model. Although the total fixed vehicle costs does not change much (+0.4%), an increase of 7.3% of the variable transport costs can be identified. From the transport performances it can be seen that the performance for all vessel types except for M2 vessels decreases as well as the transport performance of trains. This simultaneously results in an increase of 20.8% of the transport performance of trucks. This also increases the CO_2-equivalent emissions of the transport with 12.5%.

7.6.2. With hub establishment

To analyze the impact of hub establishment in the *Crisis* scenario, it is now allowed to use the established hubs. Table 7.31 gives an overview of the total costs and cost specification for transport of the shipments when the established hubs can be used. It can be seen that the total cost is 1,134 million euros, of which 56.7% of the costs are variable transport costs. If we compare the costs to the costs in the same scenario without using the established hubs, it can be seen that the total costs have decreased with 3.2%. Although hub establishment costs are applied, the fixed vehicle costs, transport costs and total transfer costs decrease. The strongest decrease of costs can be seen in the variable transport costs, which decrease with 5.4% as a result of using the established hubs. To explain this decrease, the transshipments in the terminals and the transport performances have to be analyzed first.

Table 7.31: Cost breakdown of the scenario *Crisis* where river discharge is 650 m^3/s and the rail capacity level is low. It is allowed to use established new hubs.

Total cost	**€1,134,199.94**
Fixed vehicle cost	€463,081.36
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€197,791.36
Transport cost	€643,645.57
Total transfer cost	€23,291.01
Hub establishment cost	€4,182.00

Table 7.32 shows the utilization of the terminals that are selected for transshipments. it can be seen that a large share of the cargo, 51.3%, shifts already off the waterway around Nijmegen (in BCTN Nijmegen and the Rail terminal). It can also be seen that 1,502.0 ton is shifted to continue transport by rail in the Rail terminal. This equals 9.0% of the transported cargo. The rail capacity utilization equals 100%.

All other cargo continues by road transport. In Homberg 1, another 38.5% of the cargo shifts off the waterway. The latest terminal used for transshipment is UCT Dormagen. Comparing the terminal utilization of this terminal with the case where no hubs were established, it can be seen that the terminal utilization has now increased with 1.1 percentage point. Terminals upstream of UCT Dormagen are not being used for transshipments. Comparing these results with *Regression* it can be seen that the decreasing water level puts more pressure on the terminal of BCTN Nijmegen.

Table 7.32: Terminals and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal/hub.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
BCTN Nijmegen	7,096.8 ton	58.3%	7,096.8 ton	-
Rail terminal	1,502.0 ton	6.7%	-	1,502.0 ton
Homberg 1	6,459.7 ton	57.3%	6,459.7 ton	-
UCT Dormagen	1,700.5 ton	27.9%	1,700.5 ton	-

Table 7.33 shows the transport performance of each transport modality and the total CO_2-equivalent emissions of the transport. It shows that the transport performace of M2 and M8 vessels is lower than the performance of M4 and M6 vessels. The total CO_2-equivalent emissions is 397 thousand kilograms. Comparing these transport performances to when no hubs were established, the performances of M2, M4, and M6 vessels now have been increased. The transport performance of trucks has decreased with 16.6%, while the transport performance of trains has increased with 51.8%. In this scenario it can be seen that hub establishment has a positive contribution to increasing transport by train and reducing transport by truck. Comparing the transport performance with *Regression*, it can be seen that lowering water levels result in a decrease of the transport performances of all vessel types for all transport modalities, while the transport performance of trucks and trains increases. This shows that lowering water levels require cargo to be offloaded of the waterways more downstream, so the distances of transport over land increases. The decrease in variable transport costs with establishment of hubs can be explained because transport performances of M2, M4 and M6 vessels increase as well as trains while the transport performance of trucks decreases. This results in a decrease of variable transport costs. Comparing the CO_2-equivalent emissions of transport to the emissions when no hubs were established, a decrease of 10.8% can be seen.

Table 7.33: Transport performance of each transport modality and the CO_2-equivalent emissions of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	721,657.1
M4	1,138,176.1
M6	1,725,004.0
M8	735,696.0
Truck	2,878,075.1
Train	1,094,491.1
CO_2-eq emission	397,133.0

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.1%. From the transport performances it could be seen that the transport performance of all vessel types, except for M8 vessels, increases with establishment of hubs. This simultaneously increases the transport performance of rail and reduces the transport performance of trucks which means that less cargo has to be transported over shorter distances by trucks compared to when no hubs are established. This also results in a reduction of CO_2-equivalent emissions of 10.7%.

7.7. Scenario 6: Disruption

In this scenario, the river discharge is 650 m^3/s and the capacity of the rail freight network is normal, which means that the capacity for transporting cargo by rail transport equals the amount of cargo shifted to rail in the base model at normal river discharge. In this scenario, two cases are analyzed: one where hub establishment is not allowed and one where it is allowed.

7.7.1. Without hub establishment

Table 7.34 shows the total costs and a cost specification of the cost components in the model after optimization. It can be seen that the total cost is 1,166 million euros. 57.1% of these costs are variable transport costs. It can be seen that the fixed vehicle costs of 0,47 million euros equal 40.5% of the total costs. Comparing these costs to scenario *Stagnation*, it can be seen that the lowering water levels result in an increase of 4.0% of the total costs. It can be seen that this increase is mainly caused by an increase in the variable transport costs, which increase with 5.3%.

Table 7.34: Cost breakdown of the scenario *Disruption* where river discharge is 650 m^3/s and the rail capacity level is normal.

Total cost	**€1,166,023.57**
Fixed vehicle cost	€472,913.16
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€207,623.16
Transport cost	€666,854.43
Total transfer cost	€26,255.99
Hub establishment cost	€0.00

Table 7.35 shows the terminals selected for transshipment in this scenario without using new hubs. It shows that 546.0 ton is shifted to continue transport by rail in Contargo Emmerich and 1,170.0 ton is shifted to continue transport by rail in Rhein Ruhr Terminal Gateway. This equals 10.2% of the transported cargo. The rail capacity utilization equals 97.1%. All other cargo continues by road transport. Comparing these results to the terminal utilization of *Stagnation* it can be seen that the terminal utilization of CTU Tiel, BCTN Nijmegen, and Rhein Ruhr Terminal Gateway increases, while capacity utilization of Contargo Emmerich, Nordfrost Wesel and UCT Dormagen decreases. It can be seen that the shifted cargo in the first two terminals equals 48.3% of all cargo which increased with 36.2%. This also indicates the increased pressure on the downstream terminals with lowering water levels.

Table 7.35: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
CTU Tiel	862.7 ton	14.2%	862.7 ton	-
BCTN Nijmegen	7,225.50 ton	59.3%	7,225.5 ton	-
Contargo Emmerich	546.0 ton	4.5%	-	546.0
Nordfrost Wesel	5,408.3	88.8%	5,408.3 ton	-
Rhein Ruhr Terminal Gateway	1,170.0 ton	3.2%	-	1,170.0 ton
UCT Dormagen	1,546.5 ton	25.4%	1,546.5 ton	-

Table 7.36 shows the transport performances of the modalities and the total CO_2-equivalent emissions of the transport It can be seen that the transport performances of the M4 and M6 vessels are higher compared to the M2 and M8 vessels. It can also be seen that the transport performance of trucks is much higher compared to the transport performance of trains. This is a result because of the limited capacity of available rail freight transport. The extreme low water levels require that the cargo is unloaded of the vessels downstream Kaub, because sailing past Kaub is not possible. However, the limited train availability requires more transport by truck over greater distance because it has to be

unloaded off waterborne transport more downstream. Comparing these transport performances to scenario *Stagnation*, it can be seen that although lowering water levels, the transport perforamnce of M2 vessels has increased, while transport by all other vessels has decreased. The transport performance of trucks slightly increased (1.2%) while the transport performance of trains increased with 24.3%. The CO_2-equivalent emissions in this case are 397 thousand kilograms. This is an increase of 0.8% compared to scenario *Stagnation.*

Table 7.36: Transport performance of each transport modality and the CO_2-equivalent emissions of the transport in kilograms.

Transport Modality	**Transport Performance [ton-km]**
M2	669,702.0
M4	1,074,676.3
M6	1,706,103.8
M8	735,696.0
Truck	3,233,635.7
Train	876,996.3
CO_2-eq emission	427,023.8

Comparing these results to the results of *Stagnation* and *Current ALR*, it can be seen that lowering water levels increases the total costs with 4.0% compared to *Stagnation* when the available rail capacity does not change from the current capacity. Although the total fixed vehicle costs does not change much (+2.2%), an increase of 5.3% of the variable transport costs can be identified. From the transport performances it can be seen that the transport performance of M2 vessels increases while the transport performance of the other vessel types decreases. The transport performance of trains slightly decreases while the transport performance of trucks increases with 13.6%. This also increases the CO_2-equivalent emissions of the transport with 8.3%.

7.7.2. With hub establishment

To analyze the impact of hub establishment in the *Disruption* scenario, it is now allowed to use the established hubs. Table 7.37 gives an overview of the total costs and a cost specification of the cost components when the established hubs can be used in this scenario. It can be seen that the total costs equal 1,128 million euros, which is a decrease of 3.3% in the total costs. It can be seen that the variable transport costs are 0.628 million euros, which equals 55.7% of the transport. Comparing these costs to the case without using the established hubs in the same scenario, it can be seen that the fixed transport costs are about equal, the transport costs have decreased with 5.7% while the transfer costs increased with 11.3%. The costs for hub establishment are applied as well. Although the increase in transfer costs seems large, this cost component is 27 times smaller than the variable transport cost component. The impact of the decrease in variable transport costs is therefore significant to decrease the total costs with 3.3%.

Table 7.37: Cost breakdown of the scenario *Disruption* where river discharge is 650 m^3/s and the rail capacity level is normal. It is allowed to use established new hubs.

Total cost	**€1,128,220.47**
Fixed vehicle cost	€472,040.56
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€206,750.56
Transport cost	€628,706.90
Total transfer cost	€23,291.01
Hub establishment cost	€4,182.00

Table 7.38 shows the capacity utilization of the terminals and hubs selected for transshipment of cargo.

It shows that 1767.0 ton is shifted to continue transport by rail in the Rail terminal. This equals 10.5% of the transported cargo. The rail capacity utilization equals 100%. All other cargo continues by road transport. It can be seen that the same four terminals and hubs are selected for transshipment compared with the scenario *Crisis*. However, it shows that part of the cargo that was shifted in Homberg 1 in *Crisis* has now shifted for transshipment in Rail terminal. This is a result of the increase in available rail freight capacity compared to *Crisis*. Comparing these results scenario *Stagnation*, it can be seen that here again, the terminal Contargo Ginsheim cannot be accessed anymore, because of the low available draughts near Kaub. Therefore, the pressure on the first terminals, mainly BCTN Nijmegen, increases. The terminal utilization increases with 40.1 percentage point.

Table 7.38: Terminals and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal/hub.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
BCTN Nijmegen	7,096.8 ton	58.3%	7,096.8 ton	-
Rail terminal	1,767.0 ton	7.8%	-	1,767 ton
Homberg 1	6,194.7 ton	54.9%	6,194.7 ton	-
UCT Dormagen	1,700.5 ton	27.9%	1,700.5 ton	-

Table 7.39 shows the transport performances of the transport modalities and the corresponding total CO_2-equivalent emissions of the transport. Here it can also be seen that the transport performance of M2 and M8 vessels is quite low compared to M4 and M6 vessels. The transport performance of trucks is very large. Comparing these performances to when no hubs were established, it can be seen that the transport performances of all vessel types, except for M8 vessels, have increased. This also holds for the transport performance of trains which increased with 47.5% while the transport performance of trucks decreased with 16.2%. The increase in transport performance of trains is caused by the available hub with rail infrastructure access around Nijmegen. This allows cargo that has to be transported far from the hub to be transshipped by train. The full available capacity of the rail infrastructure has been used. The amount of cargo transported by train and the great distances because sailing past Kaub is not possible, result in a strong increase in the transport performance. The increase in available capacity of the rail transport also results in a decrease in cargo that has to be transported by truck. Therefore, the transport performance of trucks decreases. From the results it can be seen that establishment of the hubs result in increased transport performances of the vessel types. This indicated that, with the established hubs, strategic cargo transshipment allows for more cargo being transported over greater distances by all vessel types except for M8 vessels. The CO_2-equivalent emission is 382 thousand kilograms. This is a reduction of 10.5% compared to when no hubs are established. This is also a result of the decrease in transport by truck and the increase of transport by train and M2, M4 and M6 vessels.

Table 7.39: Transport performance of each transport modality and the CO_2-equivalent emissions of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	721,657.1
M4	1,098,303.8
M6	1,718,735.8
M8	735,696.0
Truck	2,708.,392.9
Train	1,293,880.1
CO_2-eq emission	382,743.8

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.2%. From the transport performances it could be seen that the transport performance of all vessel types, except for M8 vessels, increases with establishment of hubs. This simultaneously increases the transport performance of rail and reduces the transport performance of trucks which means that less cargo has to be transported over shorter distances by trucks compared to when no hubs are established. This also results in a reduction of CO_2-equivalent emissions of 10.4%.

7.8. Scenario 7: Maximizing sustainable shift

In this scenario, the river discharge is 650 m^3/s and the capacity of the rail freight network is high, which means that the capacity for transporting cargo by rail transport increased with 25% of the cargo shifted to rail in the base model at normal river discharge. In this scenario, two cases are analyzed: one where hub establishment is not allowed and one where it is allowed.

7.8.1. Without hub establishment

Table 7.40 shows an overview of the total costs and a cost specification of the costs components that are considered for the total costs. It can be seen that the total costs for transport in this case are 1,161 million euros. This is an increase of 7.8% compared to *Adaptation*, which is an caused by the lowering water levels. It can also be seen that the variable costs for transport are 0.654 million euros, which equal 56.4% of the total costs. The fixed vehicle costs are 41.4%. The remainder of the costs are for transfers of the cargo to other modalities. In this case, no costs for hub establishment have to be applied. Comparing these costs to the costs of scenario, it can be seen that with lowering water discharge levels, the fixed vehicle costs increase if the rail capacity level does not change. This increase can be explained by the increase of additional trains because more cargo shifts to rail transport. The variable costs for transport increase with 5.3% compared to *Adaptation* as a result of lowering water levels. The transshipment costs increase with 3.6% as a result of the increased transport by train.

Table 7.40: Cost breakdown of the scenario *Maximum utilization* where river discharge is 650 m^3/s and the rail capacity level is high.

Total cost	**€1,161,321.15**
Fixed vehicle cost	€480,650.72
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€215,360.72
Transport cost	€654,564.51
Total transfer cost	€26,105.91
Hub establishment cost	€0.00

Table 7.41 shows the terminals selected for transshipment of the cargo, the corresponding utilization of the terminal capacity, and the amount of cargo that shifts to road and rail. It can be seen that the pressure on the downstream terminals CTU Tiel and BCTN Nijmegen is quite high: 48.1% of all the transshipments is done in these terminals. 546.0 ton is shifted to continue transport by rail in Contargo Emmerich and 1,560.0 ton is shifted to continue transport by rail in Rhein Ruhr Terminal Gateway. This equals 12.6% of the transported cargo. The rail capacity utilization equals 95.3%. All other cargo continues by road transport. Comparing these terminal utilization and transshipments to the results of scenario *Adaptation*, it can be seen that the terminal capacity utilization of the terminals CTU Tiel, BCTN Nijmegen, Contargo Emmerich, and Rhein Ruhr Terminal Gateway increases, while the capacity utilization of Nordfrost Wesel and UCT Dormagen decrease. Contargo Ginsheim cannot be accessed in this scenario anymore.

Table 7.41: Terminals selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal.

Terminal	Transferred weight	Terminal utilization	Shift to road	Shift to rail
CTU Tiel	862.7 ton	14.2%	862.7 ton	-
BCTN Nijmegen	7,192.9 ton	59.1%	7,192.9 ton	-
Contargo Emmerich	546.0	4.1%	-	546.0
Nordfrost Wesel	5,223.0 ton	85.8%	5,223.0 ton	-
Rhein Ruhr Terminal Gateway	1,560.0 ton	4.3%	-	1,560.0 ton
UCT Dormagen	1,374.4 ton	22.6%	1,374.4 ton	-

Table 7.41 shows the transport performance of each transport modality and the corresponding CO_2-equivalent emissions of the transport. It shows that again the transport performance of the M2 and M8 vessels is low compared to the performances of M4 and mainly M6 vessels. The transport performance of trucks is much higher compared to trains. This is a result of the limited available capacity of transport by train. Comparing these transport performances to the transport performances of *Adaptation* without establishment of hubs, it can be seen that, with lowering water levels, the transport performance of M2 vessels increases, while the performance of M4, M6, and M8 vessels decreases. This can be a result of the low available draughts that require cargo to be unloaded off the deeper vessels more downstream in the river. It can also be seen that, with lowering water levels, the transport performance of trucks increases with 13.8% while the performance of trains slightly decreases (0.3%). The decrease in transport performance of trains can be a result of the 95.3% utilization of the rail freight capacity. The CO_2-equivalent emissions are 413 thousand kilograms. Comparing this to *Adaptation*, the lowering water levels show an increase in CO_2-equivalent emissions of 8.2%. This increase can mainly be explained by the increase in transport performance of trucks.

Table 7.42: Transport performance of each transport modality and the CO_2-equivalent emissions of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	672,977.8
M4	1,074,686.4
M6	1,702,447.9
M8	735,696.0
Truck	3,075,856.0
Train	1,032,860.0
CO_2-eq emission	413,835.7

Comparing these results to the results of *Adaptation*, it can be seen that lowering water levels increases the total costs with 3.9% when the available rail capacity is high compared to the current capacity. Although the total fixed vehicle costs does not change much (+2.21%), an increase of 5.3% of the variable transport costs can be identified. From the transport performances it can be seen that the transport performance of M2 vessels increases while the transport performance of the other vessel types decreases. The transport performance of trains slightly decreases while the transport performance of trucks increases with 13.8%. This also increases the CO_2-equivalent emissions of the transport with 8.2%.

7.8.2. With hub establishment

To analyze the impact of hub establishment in the *Maximizing sustainable shift* scenario, it is now allowed to use the established new hubs. Table 7.43 provides the total cost and a specification of the individual cost components. It can be seen that the total costs equal 1,122 million euros. Establishment of hubs decreases the total costs with 3.5%. It can also be seen that the transport costs are 54.8% of the total costs. These decrease with 6.1% compared to when no hubs are established. The fixed vehicle costs remain quite similar (0.1%). The transfer costs decrease with 10.8%. Hub establishment costs are applied. Because of the large share of variable transport costs, the total costs decrease with establishment of hubs. A reduction in the transport costs can be explained because hub establishment allows for greater transport by waterborne transport, which will be shown from the transport performances.

Table 7.43: Cost breakdown of the scenario *Maximum utilization* where river discharge is 650 m^3/s and the rail capacity level is high. It is allowed to use established new hubs.

Total cost	**€1,122,158.55**
Fixed vehicle cost	€479,952.64
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€214,662.64
Transport cost	€614,732.90
Total transfer cost	€23,291.01
Hub establishment cost	€4,182.00

Table 7.44 shows the terminals and hubs selected for transshipments, the capacity utilization of these terminals and the cargo that shifts to road or rail in each terminal. From this, it can be seen that 52.9% of the cargo already shifts modality around Nijmegen. It can be seen that 1767.0 ton is shifted to continue transport by rail in the Rail terminal. This equals 10.5% of the transported cargo. The rail capacity utilization equals 80.0%. All other cargo continues by road transport. Comparing these results with the results of the case without hub establishment, it can be seen that the cargo shifted from waterborne transport to land modalities around Nijmegen increases from 8055.6 ton to 8863.8 ton. This is an increase of 10.0%. It can also be seen that the terminal utilization of UCT Dormagen increases with establishment of hubs. This indicates that establishment of hubs allows cargo to be transported greater distance by waterborne transport. However, because of the low available draught near Kaub, all cargo has to be shifted off the waterway downstream Kaub, because in this scenario, no vessel can sail past Kaub.

Table 7.44: Terminal and hubs selected for transshipment with the corresponding terminal utilization and the amount of cargo that shifts to road and rail specified for each terminal/hub.

Terminal	**Transferred weight**	**Terminal utilization**	**Shift to road**	**Shift to rail**
BCTN Nijmegen	6,706.8 ton	55.1%	6,706.8 ton	-
Rail terminal	2,157.0 ton	9.6%	-	2,157.0 ton
Homberg 1	6,194.7 ton	54.9%	6,194.7 ton	-
UCT Dormagen	1,700.5 ton	27.9%	1,700.5 ton	-

Table 7.45 shows the transport performance of each transport modality and the CO_2-equivalent emissions of the transport in kilograms. It can be seen that the transport performance of M2 and M8 vessels is low compared to the performance of M4 and M6 vessels. However, comparing these performances to the results without hub establishment, the performance of M2 vessels increased with 4.8%. The performance of M4 vessels slightly increases (2.2%). The performance of M6 increases slightly (1.0%). The performance of M8 remains equal. These increases indicate that establishment of hubs allow vessels to transport more cargo over greater distances over the inland waterways. Comparing the transport performance of trucks and trains, it can be seen that the performance of trucks decreases with 17.4% and the transport performance of trains increases with 43.1% by establishment of hubs. This is a result of the rail terminal that is located around Nijmegen, which increases the remaining distance that the cargo has to be transported. The CO_2-equivalent emissions of the transport equals 368 thousand kilograms. Establishment of hubs reduces the CO_2-equivalent emissions of the transport with 10.9%.

Table 7.45: Transport performance of each modality and the CO_2-equivalent emissions of the transport in kilograms.

Transport Modality	Transport Performance [ton-km]
M2	705,605.5
M4	1,098,303.8
M6	1,718,735.8
M8	735,696.0
Truck	2,539,288.0
Train	1,478,177.9
CO_2-eq emission	368,673.7

Comparing hub establishment to the system based on the existing terminals only in this scenario, the results show that allowing for hub establishment decreases the total costs with 3.4%. From the transport performances it could be seen that the transport performance of all vessel types, except for M8 vessels, increases with establishment of hubs. This simultaneously increases the transport performance of rail and reduces the transport performance of trucks which means that less cargo has to be transported over shorter distances by trucks compared to when no hubs are established. This also results in a reduction of CO_2-equivalent emissions of 3.6%.

7.9. Overview of the performance indicators

In this section, the transport performances of the transport modalities, the total costs and CO_2-equivalent emissions of the transport are visualized. Figure 7.2 shows the transport performance of all transport modalities in all scenarios with and without hub establishment. Figure 7.3 shows the share of the transport performance of a transport modality of the total transport performance. From these figures, it can be seen that with decreasing water levels, the transport performance of M2 and M4 vessels does not vary much. However, the performance of M6 vessels strongly decreases and with extreme low water levels, the performance of M8 vessels also decreases. Lowering water levels show a strong increase in the transport performance of trucks. If the rail capacity is expanded, the transport performance of trucks decreases. Comparing the transport performances of cases where hubs are established, it can be seen that the transport performance of the vessel types increases in most cases. This shows that establishment of hubs allow for different transshipment strategies that increase the cargo transport by waterborne transport. Besides, with the Rail terminal, the performance of rail transport increases, because more flow can be transported over greater distance.

However, when the river discharge is extremely low, the share in transport performances of vessels does not vary much in the different scenarios. Establishment of hubs in extreme low river discharge scenarios does not increase the transport performance of waterborne transport. In these scenarios, it can be seen that the individual performance of the different vessel types does not vary much with changes in the rail capacity. With these river discharge circumstances, waterborne transport is strongly limited.

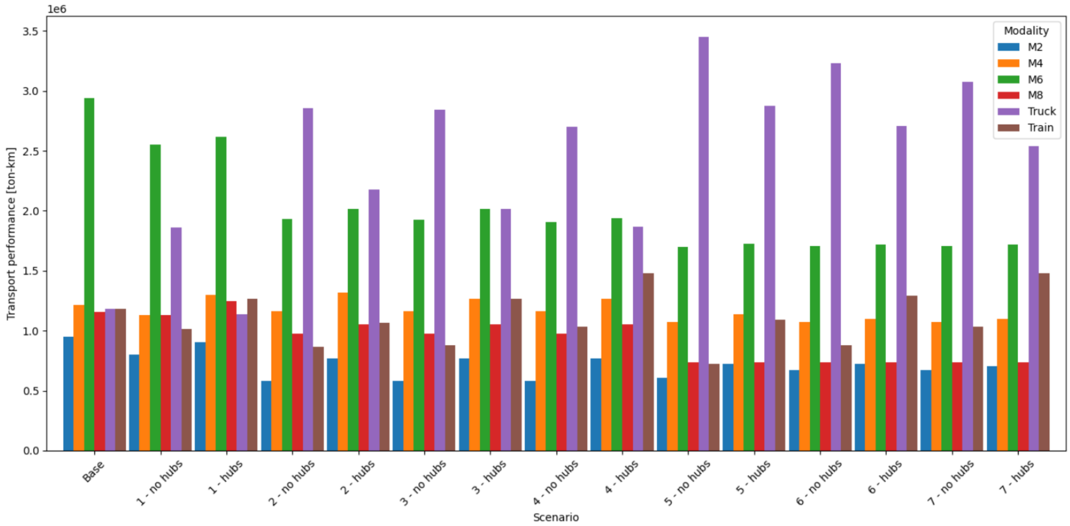


Figure 7.2: Overview of the transport performance of each transport modality in each scenario with and without establishment of hubs.

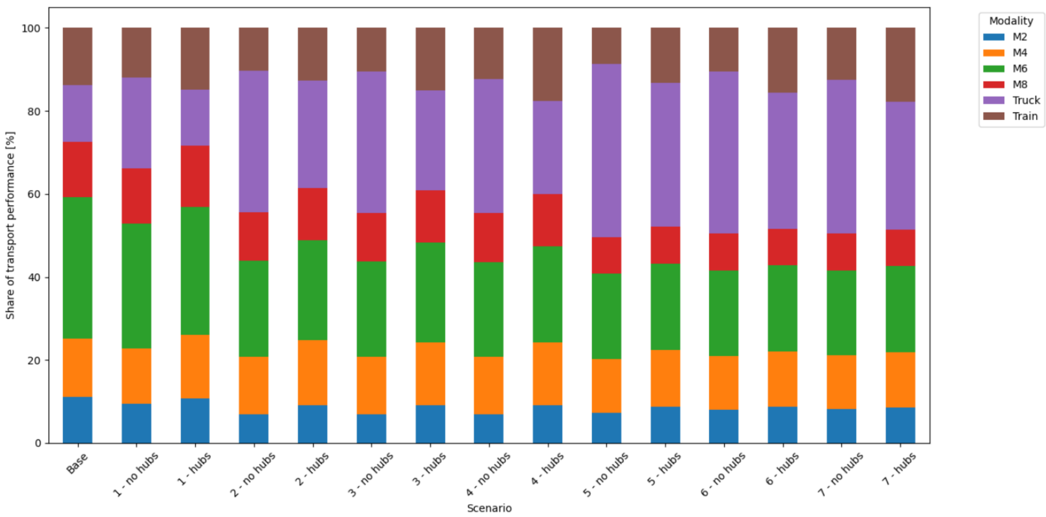


Figure 7.3: Overview of the share of transport performance of each transport modality in each scenario with and without establishment of hubs.

Comparing total transport performance across all vessel types and scenarios reveals the following. Table 7.46 shows that With lowering river discharges, the transport performance of vessels reduces with 3.1% from the normal to the Agreed Low River discharge level. A decrease to the expected Agreed Low River discharge of 2050 results in a decrease of 25.8% of the total transport performance of vessels compared to the base model. A decrease t the expected Agreed Low River discharge of 2100 results in a decrease of 33.1% in the total vessel transport performance compared to the base model. These reductions are the case when no new hubs are established and the transport capacity of the rail network remains constant. It can be seen that, for the expected low river discharge of 2050, increase of the rail capacity results in a small decrease of the total share of vessel transport performance because of the Rail terminal which allows cargo to be unloaded of vessels more downstream to be further transported by train.

Table 7.46: Overview of the share of the transport performance of all vessel types and the reduction of the total transport performance of the vessel types compared to the total transport performance of the vessel in the base model.

Scenario	Share vessel performance	Reduction to base
Base model	72.6	-
1 - no hubs	66.2	10.4
1 - hubs	71.6	3.1
2 - no hubs	55.5	25.7
2 - hubs	61.4	17.6
3 - no hubs	55.5	25.8
3 - hubs	60.9	18.4
4 - no hubs	55.3	26.1
4- hubs	60.0	19.7
5 - no hubs	49.7	34.3
5 - hubs	52.1	31.0
6 - no hubs	50.5	33.1
6 - hubs	51.6	31.7
7 - no hubs	50.5	33.2
7 - hubs	51.5	32.0

The transport performance shows what is actually transported, but changes in capacity indicate how the river is really affected by lowering river discharge levels. Table 7.47 shows the capacity in the river sections based on the number of vessels of each type as defined in the shipments and the effective loading of each type given the available draught. From this, it can be seen that the capacities in the sections of Duisburg, Köln, Kaub, Maxau and Basel, are reduced with 25.2%, 44.7%, 84.3%, 85.3% and 20.3% respectively when river discharge drops to from the normal level to the Agreed Low River Discharge. When river discharge drops further, from the normal level to 800 m^3/s, the capacities of the sections Druten, Duisburg, Köln, Kaub, Maxau and Basel drop with 8.7%, 51.9%, 76.8%, 100%, 100% and 40.5% respectively. Here it can be seen that sailing past Kaub and Maxau is with none of these vessel types possible. If the river discharge drops from the normal level to 650 m^3/s, the transport capacity at Druten, Duisburg, and Köln reduce with 17.5%, 71.4% and 96.0% respectively. It can be seen that the transport capacity near Lobith does not change, which indicates that in all river discharge levels, the available draught is sufficient for even the largest vessel type included in this research.

Table 7.47: Overview of the maximum loading [ton] given the draught and the transport capacity [ton] in that section based on the available draught and the linear relation between the loading factor and the vessel draught. The capacity is based on the vessel mix of 9 M2, 10 M4, 7 M6, and 7 M8 vessels as used in the shipments.

Section	Capacity Q = 1400	Capacity Q = 1020	Capacity Q = 800	Capacity Q = 650
Druten	47,350.0	47,350.0	43,211.3	39,084.2
Lobith	47,350.0	47,350.0	47,350.0	47,350.0
Duisburg	45,136.3	33,777.8	21,689.8	12,916.5
Köln	41,397.1	22,900.0	9,588.7	1,653.3
Kaub	28,292.2	4,445.7	0.0	0.0
Maxau	36,520.6	5,353.3	0.0	0.0
Basel	44,558.8	35,523.2	26,530.2	19,269.6

Figure 7.4 visualizes the total costs for all scenarios with and without hub establishment. It shows that with decreasing river discharge the total costs increase when the available rail capacity does not change (based on *base*, *1 - no hubs*, *3 - no hubs*, and *6 - no hubs*). It also shows that, in each river discharge scenario, the total costs decrease slightly when the available rail capacity increases. Lastly, it shows that for each scenario, hub establishment reduces the total costs compared to when no hubs are established. Comparing *1 - hubs* with *Base*, it can be seen that the total costs are about equal in case of the Current

Agreed Low River discharge with establishment of hubs compared to the current normal river discharge based on the existing terminals only.

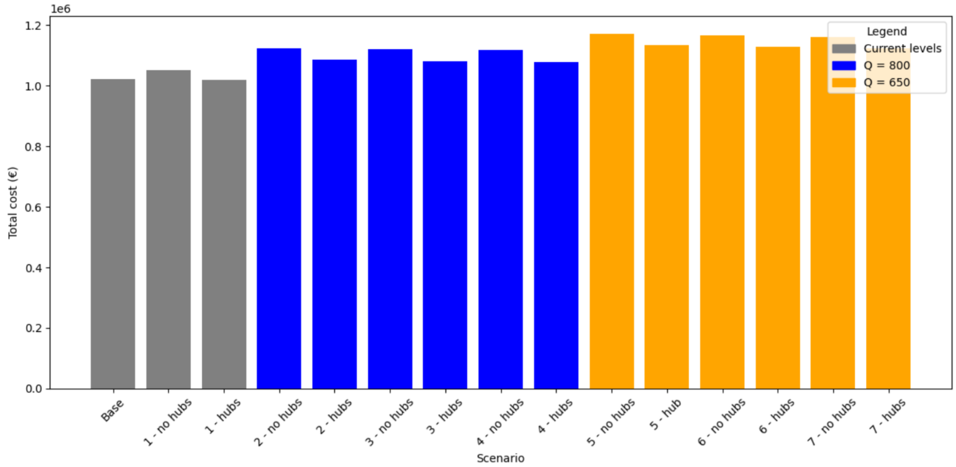


Figure 7.4: Overview of the total costs for each scenario with and without hub establishment. Grey is for the base model and the current Agreed Low River discharge. Blue is for the predicted low river discharge of 2050. Orange is for the predicted low river discharge of 2100.

Figure 7.5 visualizes the total CO_2-equivalent emissions for transport of the shipments in all scenarios. It shows that with decreasing river discharge, the total CO_2-equivalent emissions for transport increase when the available rail capacity does not change (based on *base*, *1 - no hubs*, *3 - no hubs*, and *6 - no hubs*). It also shows that, in each river discharge scenario, the total CO_2-equivalent emissions for transport decrease when the rail capacity increases. Lastly, it shows that for each scenario, hub establishment reduces the total CO_2-equivalent emissions of the transport compared to when no hubs are established. It can be seen that the total CO_2-equivalent emissions for transport in at the current Agreed Low River discharge level with establishment of new hubs (*1 - hubs*) is slightly below the CO_2-equivalent emissions of the transport in the normal river discharge with existing terminals only (*Base*).

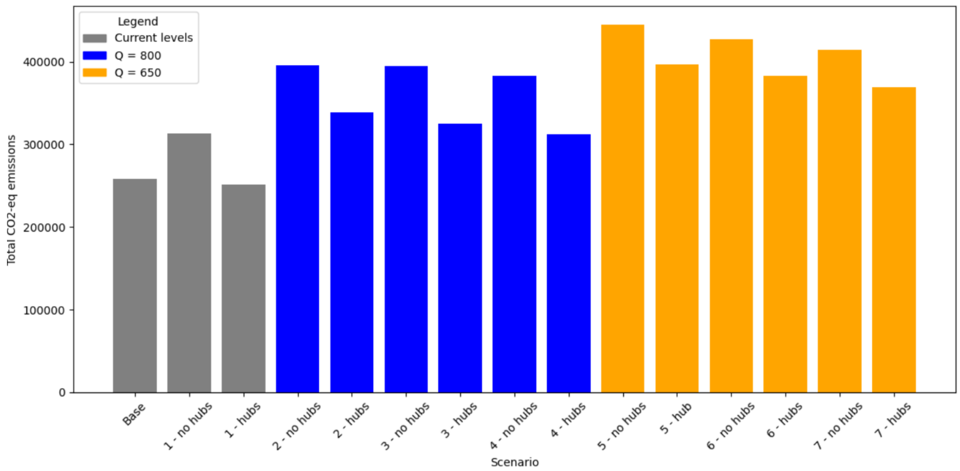


Figure 7.5: Overview of the total CO_2-equivalent emissions of the transport for each scenario with and without hub establishment. Grey is for the base model and the current Agreed Low River discharge. Blue is for the predicted low river discharge of 2050. Orange is for the predicted low river discharge of 2100.

These overviews indicate that without establishment of hubs, both the costs for transport and the CO_2-equivalent emissions of the transport will increase with decreasing river discharge levels. However, when keeping the river discharge constant, increasing the rail capacity also contributes to a slight reduction of total costs and a reduction in the CO_2-equivalent emissions. Lastly, it can be seen that establishment of hubs decreases the total costs and the CO_2-equivalent emissions even further compared to when these hubs are not established. Here it should be noted that one of the selected hubs offers access to rail infrastructure in a region without access to rail infrastructure (Nijmegen). The other hub is located in the industrial region of Duisburg in Germany where a lot of cargo has to be transported to.

7.10. Conclusion

Based on the results, conclusions can be drawn based the cost impact of decreasing water levels, the impact of the available rail capacity and the impact of hub establishment.

Cost impact of low water

Lowering the river discharge from the normal level of 1400 m^3/s to the Agreed Low River discharge level of 1020 m^3/s and further to the expected low river discharge levels of 800 and 650 m^3/s, increase the total costs between 3.3 and 6.7% per step reduction of the river discharge. The results show that variations in the rail capacity do not affect the total costs strongly. The cost increases are mainly driven by reduced vessel loading and the need for more frequent transshipments caused by the shallow available draught.

Low water levels reduce the transport performance of most of the vessel types which negatively affects the total costs. The transport performance of M2 and M4 vessels can be increased by different transshipment strategies. These different strategies allow part of the cargo of a shipment to be transported further upstream by the vessel which increases the transport performance. A decrease in the water levels, from 1020 m^3/s to 800 m^3/s, with a decrease of 15% of the available rail transport capacity would increase the transport performance of trucks with 45.2%, further increase the total costs.

Impact of the available rail capacity

Keeping discharge levels constant, it can be seen that increasing the available rail capacity increases the transport performance of trains. More cargo is shifted to rail, decreasing the transport performance of trucks. Although the variable costs are cut by shifting more cargo to rail, the total costs are still above base model because of the available draught constraint and the limited rail capacity.

Impact of hub establishment

Hub establishment shows to reduce the total costs between 3.1 and 3.6% compared to when no new hubs are established. This total costs reduction includes the daily costs for hub establishment based on the total establishment costs for 25 years. One of the new hubs is the Rail terminal which adds access to rail infrastructure around Nijmegen. With a terminal that adds rail access in this location, the distance to the final destination is more often sufficient to make it economically viable to transport cargo by train. New hubs enable longer barge legs. With establishment of the new hubs, most of the transport performances of the vessel types increased. This indicates that the hubs allow for more cargo to be transported further over the river compared to when no hubs are established in a certain scenario. Establishment of hubs decreases the CO_2-equivalent emissions between 10.5 and 18.3%.
When the river discharge is 800 m^3/s, increasing the available rail capacity decreases the CO_2-equivalent emissions with 3.0% when no hubs are established. Establishing new hubs and increasing the available rail capacity creates the potential of increasing the CO_2-equivalent emissions up to 20.9% compared to when no hubs are established and the rail capacity is not increased.

8 Discussion and Recommendations

This research investigated the impact of the establishment of new transshipment facilities along the Rhine river to enhance the drought resilience of the port-hinterland system. Drought periods generally last longer than floods and affect the inland transportation system more. For this research, IVS data, river discharge data, and data of water levels at different gauge stations on different days were used. Low river discharge scenarios affect the effective loading capacity of an individual vessel. Changing the fleet might be a short-term option, but it is not a solution in the long term. This makes studying the impact of the establishment of new transshipment facilities more meaningful.

Studies focusing on inland waterway transport as the main transport modality and combining this with the establishment of new hubs in the existing system of the Rhine river are limited. This thesis fills this gap by analyzing the impact in terms of the total cost and the CO_2-equivalent emissions of routing the shipments through the system in different scenarios based on the existing terminals only and the newly designed network. Minimization of emissions is not an objective in this research, but modalities with lower cost factors also seem to have lower emissions.

This study has significant implications for transport authorities and infrastructure owners. The results showed that without adapting the inland navigation network, decreasing water discharge levels resulted in a reduced transport performance of multiple vessel types, which lead to increase total costs. This indicates that without changes to the network, the amount of cargo transported over a certain distance decreases with lower river discharge levels. Without the establishment of hubs, the daily total costs increase up to 6.7% if water discharge levels decrease extremely. This cost increase occurs in drought periods, which are expected to occur more often and take longer in the future. If the decrease in water levels goes hand in hand with a reduction of the available rail capacity, the daily total costs increase even further. The results also showed that investing in the expansion of the rail infrastructure results in a reduction of the daily total cost of 0.4%. However, establishment of the hubs further decreases the daily total cost compared to no establishment of new hubs. With hub establishment, the total costs decrease by up to 3.6%. These results imply the value of investing in expanding infrastructure. Establishment of new transport hubs reduces the total costs more strongly than expanding rail infrastructure and also increases the transport performance of vessels. With these results, transport authorities and infrastructure owners can make better trade-offs on where to extend infrastructure and what the size of the extension should be. In these trade-offs, the location and access to rail infrastructure should be considered together. For cost minimization, only if the hub handles shipments where the final distance is greater than a certain threshold, it is valuable to have access to rail infrastructure. Besides location and access to infrastructure, the handling capacity is also important. The location is also affected by the demand for a certain region. These three factors should all be considered together. For policymakers of the European Union, it is recommended to focus on improving the drought resilience of the Rhine river because it can contribute to achieving the goals of the European Green Deal. Along with transport authorities and infrastructure owners, local governments have to be informed about the importance of establishment of transport hubs so that they can contribute in further research with verification of the location identification of the hubs. For policymakers, it is important to notice that minimization of the total costs for transport directly results in a reduction of CO_2-equivalent emissions of transport. However, it should be noted that the emissions are not necessarily minimized. Although the research has some significant implications, the research was also subject to some limitations.

One of the main limitations, as discussed in subsection 5.3.1, is that the river discharge measured at Lobith is assumed to be equal over the whole Rhine river and that the relation between river discharge and water level is assumed to be linear. This is a significant simplification of the water levels in different sections of the river, which affects the maximum effective loading capacity of the vessels. Better capturing the water flows and the relation between the water flow and level improves the accuracy of the results. Additionally, the research only focuses on the system in drought periods. The impact of the establishment of hubs on the existing terminals must also be investigated in non-drought periods.

Another limitation is that the model does not simulate the transport in time steps but only routes the transport based on the shortest path to minimize the total costs. Because of this, the availability of the rail transport capacity is only included based on the amount of transported weight and not on the arrival of trains in a terminal. From the results, it was found that the Rail terminal and expansion of rail infrastructure both contribute to the reduction of total cost. The model did not specify where rail infrastructure has to be expanded to increase the available capacity in tons. In reality, the section between Zevenaar and Oberhausen is reaching its capacity limits, which could not be taken into account in this model. This can be incorporated when the simulation is done in time steps. Simulation in time steps would make the results of this research also more meaningful when the drought period takes several consecutive days. Otherwise, it can be that the river discharge already increases before a vessel approaches a shallow section of the river.

The model only focuses on transporting cargo from the port to the hinterland. To correct for this, only 54% of the terminal capacity is allocated to import and can therefore be used for transshipment of the cargo. In reality, terminals can handle both imported and exported goods. The way terminal capacity is incorporated in the model can affect the accuracy of the results.

Another important limitation is that most of the data was only available for Lobith. This includes the IVS data. The IVS data only consists of vessels passing Lobith on each day within the data. In case of low river discharge, part of the cargo might already shift to road or rail transport from Rotterdam. Without transport statistics of road and rail transport in the same period of time, it is not known how the amount of cargo departing from Rotterdam by truck or train is affected by low water levels. It is not possible to extract from the data how the shift to rail transport, for instance, changes as a result of low water levels. With this data, the impact of drought periods on waterborne transport can be analyzed better. Moreover, although the terminal capacity was included, it was not strongly limiting the transshipments of cargo in drought periods in most of the terminals, because less cargo is transported by waterborne transport. As the IVS data did not include data on in which terminal the cargo will be transshipped, the allocation of shipments to terminals was based on the best terminal in terms of cost minimization given the available capacity. Only in some terminals, this capacity limited the shipments of cargo that have to be transshipped in the terminal. Without data of the terminals, it is not known for sure if these terminal capacity utilization values are realistic.

8.1. Recommendations

Based on these limitations, there are some recommendations for further research.

The model can be extended by also allowing for transport from the hinterland to the port. Here it should be noted that, if the hinterland-port shipments are also based on the IVS data, all exported shipments have to reach the port of Rotterdam by waterborne transport because the data is measured on the water. Additionally, the model only considers the inland navigation system in drought periods, but the impact of hub establishment should also be investigated on normal river discharge levels, because drought periods are still outnumbered by normal and high river discharge levels.

In further research, a time-based model can be developed to include the arrival of vessels, trucks and trains in the terminals. This would provide more insights in transportation times and it would limit the possibilities to transship cargo from vessels to trains because of the availability of trains. Simulating in time steps would be an important subject for further research. It will give more accurate insights in the availability of transport modalities in the terminals. Additionally, it allows for analyzing the impact of the duration of low water levels more accurately. It could be the case that the river discharge already increases before a vessel is in the shallowest section of the river. Therefore, although the results are already useful when river discharge drops, the results can be more meaningful when the river discharge is low for at least a couple of days consecutively.

One of the main recommendations from the literature is to adjust the existing vessels and to increase the size of the fleet to enhance the drought resilience of the port-hinterland system. The latter would make the fairways busier. This research studied bottlenecks based on the available draught and terminal capacities, but bottlenecks could arise based on the width of the fairways. Agent-based modeling would allow for gaining these insights in terms of width of the fairways. This approach would give meaningful insights and can be combined with other solutions from the literature to maintain sufficient available draught such as longitudinal dams. These dams narrow the width of the fairway even further.

Lastly, further research can focus on incorporating the water flow in the river more accurately. The assumption of a linear relation between the river discharge and the water level, and the assumption that the river discharge of Lobith is equal over the whole Rhine river, affect the results. Further research can contribute to the accuracy of the available draught by simulating the river from a more hydrological perspective. Due to lack of data availability, the available draught in different sections of the river was simplified because the relation between the river discharge and the water level at different gauge stations was not known. If data would be available, this can be used to simulate river flows more accurately without assuming that the river discharge of Lobith is equal in the whole Rhine river. In stead of scenarios on river discharge, a model that integrates climate projections and predictions of future river discharge levels can be used as input for more accurate future river discharge levels. To even further improve the accuracy, the river bedding and erosion of the bedding can be included.

9 Conclusion

The objective of this research is to enhance the drought resilience of port-hinterland container transport over the Rhine river from Rotterdam to the German hinterland. By doing so, the research aims to give insights in the impact of lowering river discharge levels and strategic location planning of new terminals along the Rhine river to facilitate modal shifts. Although the research focuses on the Rhine river, the method can be applied to other inland waterways as well. The main question in this research was: *How can the resilience of the port-hinterland system for container transport along the Rhine river, from Rotterdam to Germany, be enhanced through strategic establishment of modal shift hubs in response to low water levels?*

The answers to this question are explored through several sub-questions explored in this research, including:

How do low water levels affect the capacity of inland waterways?
Dropping water levels affect the capacity of inland waterways. Lower water levels decrease the available draught in the river. This affects the effective loading capacity of a vessel in a certain section of the river. Based on the composition of the fleet used in this research, the capacity at Kaub is most strongly affected when river discharge drops. At the current Agreed Low River discharge, the capacity at Kaub is reduced with 84.3% compared to the normal river discharge. If the river discharge in this section reduces further, vessels cannot sail past this section. For the sections more downstream, in Köln there is a capacity reduction of 44.7% at the current Agreed Low River discharge, 76.8% at the predicted river discharge for 2050 and 96.0% at the predicted river discharge of 2100 compared to the current normal river discharge. The transport capacity at Duisburg is smaller affected by the river discharge. With reductions of the river discharge, the transport capacity at Duisburg reduces up to 71.4% in the most extreme river discharge scenario. The section near Lobith is not affected by the reduced river discharge levels because of the sufficient available draught. Near Druten, the transport capacity reduces when the river discharge drops below the current Agreed Low River discharge level. The transport capacity reduces with 8.7% and 17.5% when river discharge is 800 m^3/s and 650 m^3/s, respectively, compared to the normal river discharge.

With reduced capacity, more trips are needed to transport the same tonnage of cargo. Increasing the fleet is only useful when the effective capacity of a vessel type is sufficient to transport cargo. For the most extreme river discharge level, changing the fleet can be useful for transporting cargo up to Köln, because some vessel types can still transport cargo in that case. However, sailing past Kaub is, at river discharge of 800 m^3/s and 650 m^3/s, not possible. Adding more vessels would increase the total transport capacity, but also make the fairways busier. Low water levels reduce the width of the fairway. Then bottlenecks cannot only be identified based on the available draught, but also on the width of the fairway.

In case of the river discharge scenario where the river discharge at Lobith would be 650 m^3/s, none of the in this research included vessel types would be able to sail past Kaub. This increases the pressure on the terminals downstream of the bottleneck. Low water requires vessels to sail at reduced speed, which decreases the capacity of the inland waterway even further. With lower water levels, the capacity of the inland waterways can be maintained by adding more vessels to the fleet.

How can the locations of transport hubs strategically be chosen to facilitate modal shift more efficiently in drought periods?
This research focused on strategic location planning of container terminals to facilitate modal shift more efficiently in drought periods. To do so, a mathematical optimization model was developed to simulate transport by waterborne, road, and rail transport from Rotterdam to the German hinterland. This mathematical model included constraints on the vessel draught, the terminal capacity, and hub selection and was the basis for scenario-based analysis, of which the results give more insights into the trade-offs on location planning for transport hubs.

It was found that Kaub is the most important bottleneck in terms of available draught. Low available draughts result in very low effective loading capacities of the vessels. Although shifts to other vessels were allowed, it was not seen because of the additional fixed vehicle costs. Hubs have to be located downstream the main bottleneck. In more extreme river discharge scenarios, the vessel draught is also strongly affected at Köln.

In drought scenarios, the establishment of hubs contributes best to reducing the total costs when located downstream of the main bottleneck of Kaub and Köln. From a cost minimization perspective, it was found that the extension of the capacity of existing terminals did not contribute to reducing the total costs. In drought periods, less cargo is transported over the Rhine river, meaning that the capacity of existing terminals does not seem to limit transshipments of cargo. The location of terminals and the accessibility to rail infrastructure depends on the shipments that have to be handled, the final destination of the shipments, and the terminals and their characteristics in the region. From a cost minimization perspective, the terminals and hubs were only used to transship cargo from waterborne transport to road and rail transport. It was found that, in terms of cost minimization, it only makes sense to shift part of the cargo to rail transport if the distance for the remaining transport is larger than the break-even distance of road transport. This indicates that having a terminal with rail access more downstream available contributes to cost minimization of transporting shipments with destinations further upstream or located far from the river.

The selected new hubs in the design did not all have rail access. Although the costs per ton-kilometer are less for rail transport than for road transport, it only makes economic sense to transport cargo by rail if the distance is great enough and the train can be filled up to almost full capacity. If the train is not completely filled up, it still makes economic sense to transport by train if the distance is greater than the break-even distance with road transport. From the research, it can be concluded that from a cost minimization perspective, the demand for certain transport modalities (specifically trains) depends on the distance to the final destinations of the shipments being handled in the terminal. If the distance to the destination is smaller than the break-even distance, it does not make economic sense to transship the cargo to freight trains. Cargo can be shifted to rail transport quite downstream in the river if it makes economic sense more than sailing further, and then be shifted to road transport. If no terminals have access to rail infrastructure in a region, it makes sense to add a terminal with rail infrastructure there if that is possible with the existing infrastructure. For a region where a lot of cargo has to be unloaded, it makes sense to add a terminal close by the center of the final destinations of those shipments.

How does the strategic location of new transshipment terminals affect the shipping costs and CO_2-equivalent emissions of the transport?
With the establishment of new hubs, the total costs for transporting the shipments decrease if the available rail capacity remains constant. When the river discharge at Lobith is 800 m^3/s, establishment of new terminals reduces the transport costs by 11.2% and the overall costs by 3.4%. When the river discharge at Lobith is 650 m^3/s, establishment of new terminals reduces the transport costs by 12.8% and the overall costs by 4.7%.

When selecting routes and strategic modal shift in a way to minimize the total costs, the CO_2-equivalent emissions of the transport reduce more strongly with the establishment of new hubs compared to the existing terminals only. Cheaper transport options (waterborne transport and rail transport) also have lower emissions per ton-kilometer compared to transport by truck. Establishment of hubs increases the transport performance of waterborne transport in the case of low river discharge. Therefore, more cargo is transported over greater distances over water. When the river discharge at Lobith is 800 m^3/s, establishment of new terminals reduces the CO_2-equivalent emissions of the transport by 9.8% compared to transport in the same system without establishment of new hubs. When the river discharge at Lobith decreases to 650 m^3/s, establishment of new terminals reduces the CO_2-equivalent emissions of the transport with 3.6%. In the scenario of 650 m^3/s, the reduction in CO_2-equivalent emissions of the transport is smaller, because the transport performance by truck increases while the transport performance by truck in the scenario of 800 m^3/s decreases.

What trade-offs must policymakers consider when deciding whether and where to invest in new transshipment infrastructure?
In this research, the selection of hubs was approached from a total cost minimization point of view. Shipments are only routed through terminals if that reduces overall transport costs. Although reduction of CO_2-equivalent emissions was not an explicit objective, cost minimization strategies incidentally led to a decrease in emissions.

The hub characteristics considered in this study include establishment and expansion costs, geographic location, handling capacity and the accessibility to infrastructure.

Expanding available rail capacity contributes to cost reductions in port-hinterland transport. However, this research does not account for the costs or specific characteristics of rail expansion projects. Greater cost savings can be achieved when hubs are optimally located and have access to appropriate infrastructure to allow for multi-modal transport. From a network design perspective, key considerations include hub location, capacity, and rail accessibility.

These factors are interconnected. For example, cargo can be transshipped to rail only if the hub has rail access and the remaining transport distance is long enough to make rail economically viable compared to road. In this context, hubs must be located downstream of key bottlenecks, such as Kaub, and under more extreme river discharge conditions, downstream of Köln.

Furthermore, terminals with rail access are better positioned further downstream, where longer road distances to final destinations favor rail from a cost perspective. The shipments allocated to a terminal affect the size of the handling capacity. The size of the handling capacity affects the establishment costs. Larger terminals require higher investments.

These factors are interdependent, which highlights the importance of evaluating trade-offs from a systems perspective.

To conclude, strategic establishment of transshipment facilities not only contributes to the cost-effective inland container logistics but also supports sustainable transport along the Rhine river. In terms of total cost minimization, the results demonstrated that strategic establishment of new modal shift hubs along the Rhine significantly enhances the transport performance of vessels, which has both economic and environmental advantages. It was found that the capacity of existing terminals does not strictly limit the transshipments because the total transported amount of cargo, on days with low river discharge, is smaller compared to days with normal river discharge. However, the location of the terminal, as well as the modality options of the terminal and the existence of terminals in the region, does play a significant role in minimizing the total costs for transport. Strategic allocation of transshipments to terminals is based on the mode availability in the terminal, the distance to the final destination of the cargo, and the handling capacity of the terminal.

By enabling cargo to travel greater distances by inland waterway, these hubs contribute to reducing the total costs for shipping cargo from Rotterdam to the German hinterland and improve the utilization of waterborne transport. Along with the cost minimization of establishing new hubs, the results also showed that the CO_2-equivalent emissions of the total transport are reduced.

The research indicated that no cargo can pass the Rhine river near Kaub on the vessel types included in this research when the river discharge drops too far. However, the hub lifespan is considered 25 years, while no sailing past Kaub was seen in the river discharge scenario of 2100.

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A

Container terminals

Table A.1: Container terminals along the Rhine river that have direct access to the Port of Rotterdam (Port of Rotterdam, n.d.-b). RA means if a terminal has direct access to rail. NC is the number of container cranes available to (un)load vessels, trains and trucks.

Code	Terminal	Coordinates	RA	NC
2	CTU Tiel	51.91731987365765, 5.4427073110026765	No	1
3	BCTN Nijmegen	51.860157994883366, 5.83100699750661	No	2
4	Contargo Emmerich	51.83107529765252, 6.254066582163171	Yes	2
5	Nordfrost Wesel	51.63822135578276, 6.619023443343932	No	1
6	Trimodal terminal Deltaport	51.6227909473084, 6.608725435545752	Yes	1
7	Contargo Emmelsum	51.62302912843705, 6.609226575631812	Yes	1
8	Multimodal terminal Duisburg	51.52246398565745, 6.710710624478048	Yes	1
9	Hutchison Ports DeCeTe Duisburg	51.45036424226572, 6.746898512829989	Yes	3
10	Rhein Ruhr Terminal (Home)	51.38036551390919, 6.734683530017634	Yes	2
11	Duisburg Trimodal Terminal (D3T)	51.39771513642397, 6.735899626321038	Yes	2
12	Duisburg Intermodal Terminal (DIT)	51.390290590126206, 6.730181120826731	Yes	4
13	Rhein Ruhr Terminal (Gateway)	51.457295245972034, 6.761635679348946	Yes	6
14	Krefelder Container Terminal	51.3459849014699, 6.663825837963426	Yes	1
15	Düsseldorfer Container Haven (DCH)	51.217964513720865, 6.735287212819475	Yes	2
16	Contargo Neuss	51.21218437825651, 6.708980071830189	Yes	3
17	Optimodal Neuss	51.21402438559923, 6.707975828161335	Yes	2
18	UCT Dormagen	51.14086845006421, 6.80634072630943	No	1
19	CTS container terminal	50.97635252618803, 6.977096507072061	Yes	2
20	AM Zehnhoff Söns GmbH (Bonn)	50.758191034086735, 7.089112224443492	No	1
21	Haeger & Andernach	50.43974699961313, 7.429079941619934	Yes	2
22	Contargo Koblenz	50.39407096523736, 7.589151428124458	Yes	2
23	Terminal Mainz Frankenbach	50.02296303999273, 8.244679382081568	Yes	2
24	Contargo Ginsheim	49.9980616978492, 8.310255099271258	No	1
25	Gut Gernsheimer Umslag	49.75480835855284, 8.479782182069709	Yes	1
26	Rhenania Worms	49.63758969116856, 8.374674682064477	Yes	2
27	DP World Mannheim	49.49710169677293, 8.46143120904514	Yes	1
28	Contargo Mannheim	49.490662139076015, 8.452740814825855	Yes	4
29	Ludwigshafen am Rhein	49.45869341958505, 8.436435769201966	Yes	2
30	DP Gemersheim	49.22999752643106, 8.37742289923736	Yes	3
31	Wörth am Rhein	49.05981828518756, 8.29882579717565	Yes	3
32	Contargo Karlsruhe	49.017146970771684, 8.320574453201736	Yes	1
33	Lauterbourg Rhine terminal (LRT)	48.954835064455, 8.185313131758168	Yes	1
34	Euro Terminal Kehl	48.59653847458052, 7.817428999209673	Yes	4
35	Strasbourg Terminal Nord	48.58559997221303, 7.792010419159928	Yes	3
36	Strasbourg Terminal Sud	48.538634675895324, 7.7944550550295295	Yes	2
37	Port Rhenan de Mulhouse	47.79127695128265, 7.522878514383266	Yes	1
38	Contargo Weil am Rhein	47.60758983964473, 7.592447437216581	Yes	1
39	Contargo Basel	47.58721004143243, 7.598994768482094	Yes	2
40	Swissterminal Basel	47.584198431312124, 7.587775583824066	Yes	1

B

Potential hubs

Nijmegen

Table B.1 gives an overview of the potential transport hubs downstream Nijmegen. For each hub, the number of cranes and the surface of the hub area, and if the hub is accessible by road or rail is provided.

Table B.1: Characteristics of the potential hub locations downstream Nijmegen that are located along the Rhine river.

Code	Potential hub	Number of cranes [#]	Hub area [m^2]	Road access	Rail access	Time-eq establishment cost
100	Area next to Druten Wijgula B.V.	2	68.000	Yes	No	2634
101	River Harbour Waalbandijk	1	52.000	Yes	No	1869
102	IJzendoorn	1	45.000	Yes	No	1654
103	Potential rail terminal	2	137.000	Yes	Yes	2374

The Port of Nijmegen, Druten Wijgula B.V. and Deelens Transport Waalbandijk have been removed of the list as suggested by Van der Plas (2024) as these locations were already being used for other purposes. Railterminal Gelderland Valburg has been removed, since it was located 2 kilometers away from the river. Instead, a potential rail terminal has been added to the list that is located along the river, as well as the rail. This location has sufficient space available to facilitate loading the trains. The location next to Druten Wijgula B.V. has also been added as this is fallow land.

Duisburg

Table B.2 gives an overview of the potential transport hubs downstream Duisburg. For each hub, the number of cranes and the surface of the hub area, and if the hub is accessible by road or rail is provided.

Table B.2: Characteristics of the potential hub locations downstream Duisburg that are located along the Rhine river.

Code	Potential hub	Number of cranes [#]	Hub area [m^2]	Road access	Rail access	Time-eq establishment cost
104	Area next to Homberg	1	50.000	Yes	No	1808
105	Area next to Homberg	2	100.000	Yes	No	2739
106	Area next to Homberg	3	150.000	Yes	No	2794
107	Area next to DGT	1	50.000	Yes	Yes	1819
-	HGK intermodal terminal	2	80.000	Yes	Yes	0
-	Multimodal terminal	1	30.000	Yes	Yes	0

The locations Nordhafen and Südhafen Duisburg have been removed of the list as suggested by Van der Plas (2024) as these locations were already being used for other purposes. Multimodal Terminal Duisburg is also being used for other purposes and does not have space for vessels to stop at the terminal. Homberg is the only potential hub in the list that is currently an empty area so this location will have high establishing costs.

The DUSS-terminal is a rail terminal next to the hub of Hutchison ports. The DUSS-terminal does not have any connections to the water itself and can, therefore, only be chosen in addition to the Hutchison port.

Kaub

Table B.3 gives an overview of the potential transport hubs downstream Kaub. For each hub, the number of cranes and the surface of the hub area, and if the hub is accessible by road or rail is provided. It should be noticed that the potential hubs for the bottleneck of Kaub are all located around Koblenz. In Koblenz, the fairway is deeper compared to the fairway in Kaub (see Appendix B). Another advantage is that the Rhine-Alpine corridor passes Koblenz, so most potential hub locations have access to rail transport.

Table B.3: Characteristics of the potential hub locations downstream Kaub that are located along the Rhine river.

Code	Potential hub	Number of cranes [#]	Hub area [m^2]	Road access	Rail access	Time-eq establishment cost
108	Area next to Koblenz Raptors	1	80.000	Yes	Yes	2728
109	Area next to Koblenz Raptors	2	100.000	Yes	Yes	2739
110	Area next to Koblenz Raptors	3	130.000	Yes	Yes	3671
111	Area next to shunting yard	1	15.000	Yes	Yes	882
112	Area next to shunting yard	2	25.000	Yes	Yes	1539
113	Area next to Im Sändchen	1	40.000	Yes	No	1808

The locations Koblenz Raptors, Rhein Marina Kaiser Wilhelm, and Rhein Lache Koblenz have been removed of the list as suggested by Van der Plas (2024) as these locations were already being used for other purposes.

Time equivalent cost determination

Based on costs for expanding the BCTN terminal in Nijmegen and the establishing costs for the Gateway terminal in Duisburg, cost figures have been estimated per square meter of building an inland terminal. These cost estimations can be seen in Table B.4. Economies of scale are considered, so if a terminal is larger, the costs per square meter decrease. The terminal of BCTN has been expanded with about 20.000 square meters and the Duisburg Gateway terminal is over 200.000 square meters large. Therefore, the lower and upper bound are set based on these cost figures. Accessibility of rail infrastructure costs 500 euros per meter rail. A ship-to-shore crane costs 2.5 million euros.

Table B.4: Time equivalent cost determination per square meter per size of terminal.

Size [m^2]	20.000	50.000	100.000	150.000	> 200.000
Cost [EUR/m^2]	350	280	200	120	70

Extension of existing terminals

Based on availability of free space in the area surrounding existing container terminals, some terminals were selected for potential extension. Depending on the amount of free space around a terminal, the terminal can be extended with one or two container cranes. Extension of the terminal includes construction of quay, storage area, optional rail infrastructure (if the terminal already has access to rail infrastructure) and container cranes. The terminals that can be extended, and the corresponding extension costs can be seen in Table B.5.

Table B.5: Overview of existing terminals that can be extended with the number of container cranes (and quays), the additional capacity and the time-equivalent (daily) extension costs.

Terminal	Extension with	Additional capacity	Cost per day
BCTN Nijmegen	1 crane	11275 ton	1041
BCTN Nijmegen	2 cranes	22550 ton	1890
Nordfrost Wesel	1 crane	11275 ton	1808
Contargo Emmelsum	1 crane	11275 ton	841
Rhein Ruhr Terminal	1 crane	11275 ton	1041

C

Depth of the fairway

Figure C.1 shows *Doorvaarthoogte van de brug* (clearance of the fairway), *Diepte van de vaargeul bij OLR* which is the depth of the fairway at Agreed Low River Discharge, 1020 m^3/s and *Vaargeulbreedte bij OLR* (Width of the fairway at Agreed Low Water Discharge) of the Rhine river from Rotterdam to Basel.

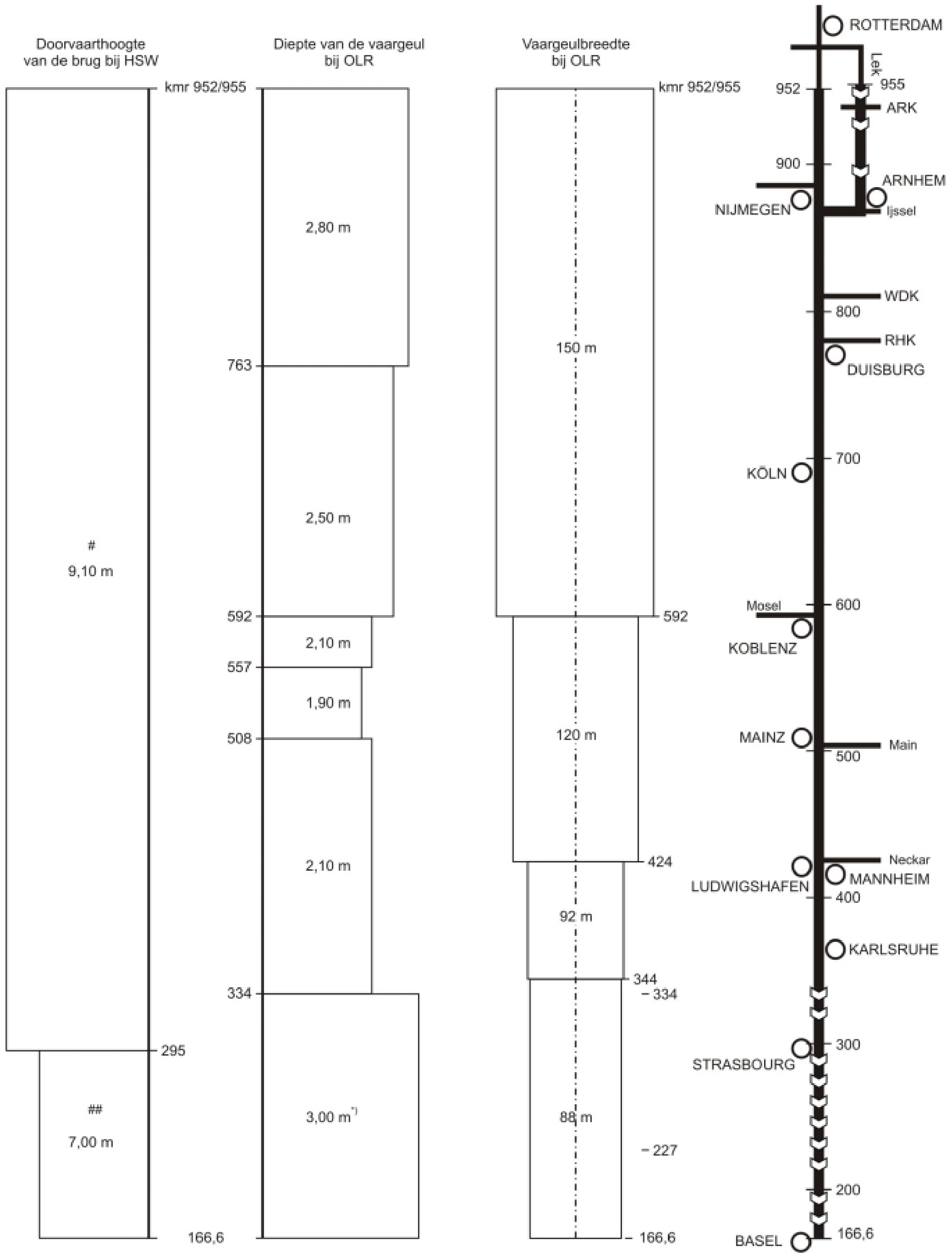

Figure C.1: Fairway information of the Rhine river from Rotterdam to Basel.

Table C.1 shows the the linearization of the available draught of different sections in the Rhine river. The available draught has been measured on two different days. The river discharge of 1363 m^3/s at Lobith and the corresponding available draughts on the different gauge stations were measured on 28 May 2025. The river discharge of 1063 m^3/s at Lobith and the corresponding available draughts on the different gauge stations were measured on 14 April 2025. The column *Difference* shows the difference in available draught for the two different river discharge level. The *Difference per m^3/s* has been computed by dividing the difference in the available draught by the difference in river discharge (=300 m^3/s). The *Difference per m^3/s* can be used to compute the available draught on different river discharge levels. The available draught at Druten when the river discharge is 1400 m^3/s would then become $423 + 0.2067 \cdot (1400 - 1363) = 431$cm. This simplification in addressing the available draught results in a small error to the available draught value (<0.5%).

Table C.1: Linearization of the available river discharge level for different gauge stations.

Gauge station	Available draught Q = 1363	Available draught Q = 1063	Difference	Difference per m^3/s
Druten	423	361	62	0.267
Lobith	532	468	64	0.213
Duisburg	320	261	59	0.1967
Köln	282	222	60	0.20
Kaub	223	161	62	0.2067
Maxau	253	167	86	0.2867
Basel	315	267	48	0.16

D

Shipment Selection

Table D.1 shows all days in the data where the river discharge was measured between 1010 and 1030 m^3/s. It shows that from these days, most vessels with most unique destinations and second most total transported weight passed Lobith on 27 November 2021. Therefore, this day was selected to simulate the shipments.

Table D.1: Days where river discharge at Lobith was measured between 1010 and 1030 m^s/s.

Date	Vessels	Destinations	Transported weight
2018-07-30	30	4	16692
2018-09-09	17	3	5679
2018-09-10	23	3	10269
2018-12-05	16	3	6705
2021-11-27	**33**	**6**	**15991**
2021-11-28	10	4	3146
2022-09-11	11	3	1097
2022-09-12	17	3	6243
2023-10-17	13	4	3938
2023-10-19	9	3	4529

E
Manual Checks on Results

Table E.1 shows an example, shipment 0, where 557 ton is transported from Rotterdam to Oberhausen via Nordfrost Wesel. The cargo departs Rotterdam by M8 vessel as determined based on the IVS data. The cargo is transshipped to trucks Nordfrost Wesel to its final destination. The final destination and shipment label are preserved when cargo is being transshipped from one modality to another.

Table E.1: Results of shipment 0 that transports 557 tons from Rotterdam to Oberhausen via Nordfrost Wesel (terminal 5).

— Vessel Shipment shipment 0 (Type: vessel_m8) —
Arc (1 -> 2), mode: vessel (Vessel Type: vessel_m8), Flow: 557.00
Arc (2 -> 3), mode: vessel (Vessel Type: vessel_m8), Flow: 557.00
Arc (3 -> 4), mode: vessel (Vessel Type: vessel_m8), Flow: 557.00
Arc (4 -> 5), mode: vessel (Vessel Type: vessel_m8), Flow: 557.00
Arc (5 -> Oberhausen), mode: road, Flow: 557.00

Figure E.1 visualizes the information from Table E.1.

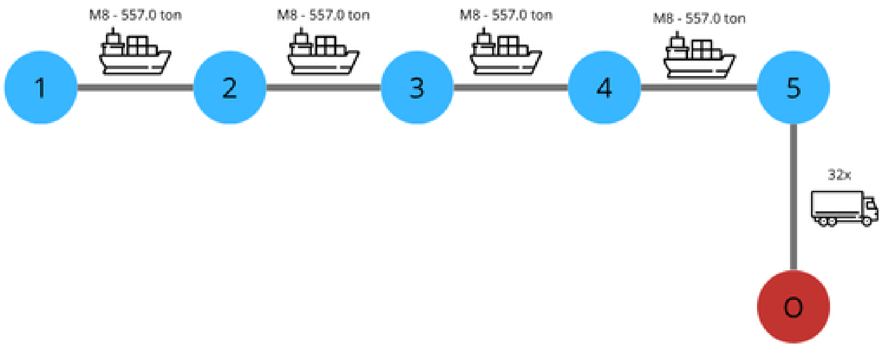

Figure E.1: Visualization of the manual check of shipment 0

Table E.2 shows another example of a shipment. In this shipment, 824 tons of cargo are transported from Rotterdam to Mannheim. In Multimodal Terminal Duisburg, a shift of 390 ton to train takes place. The break-even distance of a full train and transport by trucks is 248 km. Distances by train above 248 km is economically beneficial compared to transport by trucks. The Euclidean distance from Optimodal Neuss to rail yard Mannheim is 399,65 km. The remaining part is further being transported by vessel. Then in the terminal Contargo Koblenz, the remaining 434 ton of cargo is transported to Mannheim by truck. The second column of the table shows the effective capacity. Comparing the flows with the effective capacity, it can be seen that the effective capacity cannot be exceeded. Therefore, the model had chosen to shift part of the cargo to rail transport already in the Multimodal Terminal Duisburg. It can be seen that somewhere before terminal Optimodal Neuss (terminal 17) a shift had to be made, because the initial flow of 824 ton would exceed the effective loading capacity of 534 ton after terminal Optimodal Neuss. The sum of the cargo entering the final destination equals the initial flow departing from Rotterdam (terminal 1).

Table E.2: Results of shipment 28 that transports 824 tons from Rotterdam to Mannheim via Multimodal Terminal Duisburg (terminal 8) and Contargo Koblenz (terminal 22).

— Vessel Shipment shipment 28 (Type: vessel_m6) —	Effective capacity vessel
Arc (1 -> 2), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	2284
Arc (2 -> 3), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	3320
Arc (3 -> 4), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	1409
Arc (4 -> 5), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	1409
Arc (5 -> 6), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	1409
Arc (6 -> 7), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	1409
Arc (7 -> 8), mode: vessel (Vessel Type: vessel_m6), Flow: 824.00	1409
Arc (8 -> 9), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (8 -> Mannheim), mode: rail, Flow: 390.00	
Arc (9 -> 10), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (10 -> 11), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (11 -> 12), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (12 -> 13), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (13 -> 14), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (14 -> 15), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (15 -> 16), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (16 -> 17), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	1068
Arc (17 -> 18), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	534
Arc (18 -> 19), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	534
Arc (19 -> 20), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	534
Arc (20 -> 21), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	534
Arc (21 -> 22), mode: vessel (Vessel Type: vessel_m6), Flow: 434.00	534
Arc (22 -> Mannheim), mode: road, Flow: 434.00	

Figure E.2 visualizes the information of the example of shipment 28 as shown in Table E.2.

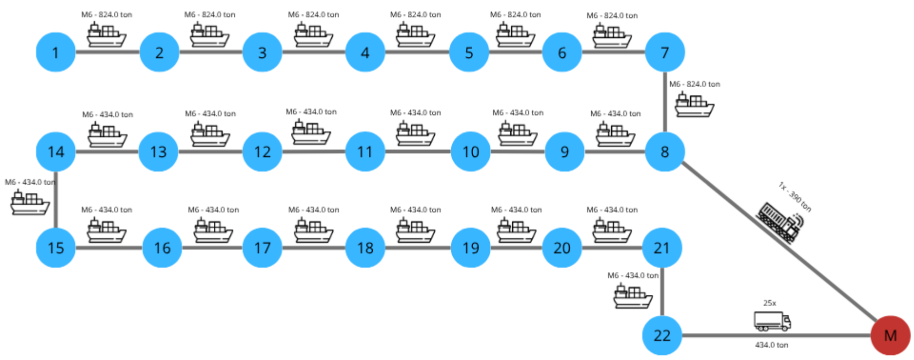

Figure E.2: Visualization of the manual check of shipment 28

Table E.3 shows that the loading of the vessels departing from Rotterdam equals the loading factor as derived from the IVS data multiplied by the vessel capacity.

Table E.3: Loading of the departing vessels based on the loading factor of the vessel and the vessel capacity.

Vessels departing from Rotterdam	LF · vessel capacity
ship_0 to Oberhausen: Arc (1 -> 2), mode: vessel (Vessel Type: vessel_m8), Flow: 557.00	0.2027·2750=557
ship_1 to Oberhausen: Arc (1 -> 2), mode: vessel (Vessel Type: vessel_m8), Flow: 511.00	0.1858·2750=511
ship_2 to Oberhausen: Arc (1 -> 2), mode: vessel (Vessel Type: vessel_m8), Flow: 562.00	0.2043·2750=562

Table E.4 shows again the total cost of the base model. It can be seen that in this simulation, extension of existing terminals and establishment of new hubs was not allowed. Therefore, these cost terms are 0.

The other cost factors have been manually checked as follows. The acquisition costs are based on a multiplication of the number of vessels of each type, trucks and trains multiplied by its acquisition cost factor. The transport costs were checked by multiplying the transport performance (in ton-kilometer) of each transport modality with the cost factor for transporting a ton cargo a kilometer by a transport modality. The total transfer costs is the weight that has to be transferred divided by the crane rate and multiplied by the transfer cost factor.

Table E.4: Cost breakdown of the base model at river discharge of 1400 m^3/s.

Total cost	**€1,015,650.29**
Fixed vehicle cost	€472,215.08
- Fixed costs vessels	€265,290.00
- Fixed costs trucks and trains	€206,925.08
Transport cost	€525,406.09
Total transfer cost	€18,029.12
Hub establishment cost	€0.00
Terminal extension cost	€0.00

Table E.5 shows the terminal utilization of transshipments made in the terminals selected by the model. It shows that the terminal capacity cannot be exceeded. The capacity of the terminal Nordfrost Wesel is fully used.

Table E.5: Transferred weight in the selected terminals and the corresponding terminal utilization when the river discharge at Lobith is 1400 m^3/s.

Terminal	**Transferred weight**	**Terminal utilization**
BCTN Nijmegen	2758.5 ton	22.7%
Contargo Emmerich	1767 ton	14.5 %
Nordfrost Wesel	6088.5 ton	100%
UCT Dormagen	1955 ton	32.1%
Contargo Ginsheim	4190 ton	68.3%

F

Scientific paper

Increasing drought resilience of the port-hinterland system. A case study on the Rhine river.

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Abstract Future demand for container transport is expected to increase, placing pressure on the port-hinterland system of the Rhine river. To meet European climate goals and relieve the congested road freight system, inland waterway transport (IWT) is promoted as a sustainable alternative. However, IWT is vulnerable to low water levels as a result of climate change, as evidenced by significant drought periods in 2018. This research investigates how the strategic establishment of transshipment hubs can enhance the climate resilience of the port-hinterland system of the Rhine river under varying river discharge scenarios. The focus is on three critical bottlenecks in terms of available draught: Druten, Duisburg, and Kaub. This study quantifies the impact of new hubs on the total cost and CO_2-equivalent emissions by developing a mathematical location routing model, which is used for a scenario-based analysis with varying river discharge levels and rail capacity levels. Results show that hub establishment significantly reduces both total transport costs and CO_2-equivalent emissions during low discharge scenarios, without requiring expansion of existing terminals. The establishment of hubs depends on location and multimodal accessibility, with rail connections only becoming economically viable when the remaining hub-destination distance exceeds certain distance thresholds. The findings provide actionable insights for policymakers and transport authorities on strategic decisions of infrastructure investments to improve the climate-resilience of freight transport along the Rhine corridor to minimize total costs, reduce CO_2-equivalent emissions, and relieve congested road networks.

Keywords: Drought Resilience | Inland Waterway Transport | Cost Efficiency | Multimodal Location Routing Problem | Rhine River

F.1. Introduction

Future demand for container transport is expected to grow in the coming years. In the Port of Rotterdam, 54% of the cargo handled consists of goods that need be transported to the hinterlands (Port of Rotterdam, n.d.). Inland waterway projects aim to promote transport via rivers to reduce transport emissions. The European Commission has set a goal to shift 75% of road freight over long distances to other, more sustainable transport modalities (European Commission et al., 2023). While inland waterway transport (IWT) is a more sustainable alternative to road freight transport, it is less resilient to climate change. The drought periods in 2018 highlighted this with a shift in the market share of IWT to road transport because of the low water levels. The amount of transported cargo did not return to the same level as before the drought periods. Low water levels directly affect the effective capacity of individual vessels. Transporting the same amount of cargo in a drought period, therefore, requires multiple trips and different loading strategies.

The water discharge, which is the amount of water that flows past a measurement point per second, is strongly related to the water levels. Water discharge is expected to decrease in the future. Drought periods are expected to occur more often and last longer. To contribute to the objectives of the European Commission, this research focuses on the most important European inland waterway: the Rhine river. To make the port-hinterland system more robust and resilient against climate change, this research aims to enhance the resilience of the Rhine river by analyzing the impacts of the strategic establishment of transshipment hubs in response to low water levels. To assess this, data analysis has been conducted to analyze the impact of water discharge levels on inland waterway transport from the transport statistics and at different water discharge levels. This analysis is used to define input parameters for the mathematical location routing model, which simulates the multi-modal transport of a set of shipments from the origin to the corresponding destinations. This model is the basis for the scenario-based analysis, in which water discharge levels and the available rail capacity vary.

The remainder of this paper is structured as follows. Section F.2 gives an overview of the existing literature. Section F.3 describes the data used for this research. Section F.4 provides a more detailed description of the network. Section F.5 gives an in-depth description of the mathematical model. Section F.6 describes the scenarios used for the scenario-based analysis and provides the results of the analysis. This section includes a brief discussion on the results. Section F.7 discusses the implications of the results. Section F.8 concludes the main findings and provides recommendations for future research.

F.2. Literature Review

Inland waterway transport is more sensitive to climate-related changes than other modalities. Fluctuations in river discharge—especially low water levels—can significantly reduce vessel loading capacity and transport reliability (Hendrickx & Breemersch, 2012). As water levels drop, cargo often shifts to road transport, which is more flexible but less sustainable and more expensive (Bedoya-Maya et al., 2024). Rail can partially absorb the displaced volume, but is limited by the available capacity and slot constraints (Gandhi et al., 2024). As a result, most studies on modal shift have focused on road and rail as dominant transport modes, with less attention to adaptation within IWT itself.

Despite its environmental and infrastructural advantages, the full potential of IWT remains underutilized (Bedoya-Maya et al., 2025). Recent studies have emphasized that hub establishment can increase the resilience of inland waterway networks in drought conditions. For example, Hekkenberg (2015) showed that optimized fleet composition and adequate transshipment facilities can significantly enhance drought resilience. Gobert and Rudolf (2023) further emphasized that strengthening intermodal connections along river corridors is key for drought adaptation. Moreover, Calderón-Rivera et al. (2024) and Jiang et al. (2024) found that promoting modal shift to waterways not only supports cost efficiency but also reduces congestion, CO_2 emissions, and infrastructure wear.

However, the exact impact of hub establishment on the Rhine port-hinterland system remains underexplored. While several bottlenecks and potential hub locations have been identified along the Rhine river (Van der Plas, 2024), most research has not yet assessed how hubs affect the transportation system in low water conditions.

From a modeling perspective, only a limited number of studies incorporate low water levels into multimodal transport optimization. Nur et al. (2020) modeled IWT under fluctuating water levels, accounting for barge capacity reductions and terminal capacity constraints. Aghalari et al. (2021) explored the integration of IWT into broader multimodal systems, yet did not fully consider the dynamic impact of drought on vessel performance. More general multimodal models, such as those by Fazayeli et al. (2018) and Alumur et al. (2012), tend to focus on mode selection and routing without capturing hydrological dependencies.

Hub location optimization has received more attention in other contexts. Racunica and Wynter (2005), Arnold et al. (2004), and Bhurtyal et al. (2024) developed models for determining optimal terminal locations under cost and demand uncertainty, typically emphasizing rail or road logistics. Binsfeld et al. (2024) focused on the West German canal system and proposed an integrated model to minimize total cost and emissions during infrastructure disruptions. This study showed that hub placement can reduce costs by up to 28%. Still, most models assume fixed vehicle capacity for vessels, neglecting the effect of river discharge on vessel loading.

While Van der Plas (2024) applied multi-criteria decision analysis to identify hub locations along the Rhine, constraints on terminal capacity and effective vessel capacity, and optimization of allocating shipments to terminals were not addressed. This highlights a key research gap. Research that integrates hub location, terminal throughput, and draught-dependent vessel capacity to evaluate drought resilience in multimodal transport systems is still limited. Table F.1 provides a general overview of the existing research on hub location and routing for multimodal transport. Table F.1 serves as a comparative reference for the main characteristics of each study.

Table F.1: General overview of the existing literature on multi-modal routing and hub establishment in port-hinterland transportation systems.

Reference	Available draught	Terminal capacity	Hub establishment	Transport modes			Solution Approach*
				Waterways	Road	Rail	
Arnold et al. (2004)			✓		✓	✓	ILP
Racunica and Wynter (2005)			✓		✓	✓	MINLP
Alumur et al. (2012)					✓		MILP
Caris et al. (2012)							
Sun and Lang (2015)		✓			✓	✓	MINLP
Marufuzzaman and Eksioglu (2016)		✓	✓	✓	✓	✓	MILP
Li and Zhang (2020)		✓			✓	✓	MILP
Fazayeli et al. (2018)			✓	✓	✓	✓	MINLP
Ahadi et al. (2018)	✓	✓		✓			MILP
Nur et al. (2020)	✓	✓		✓	✓		MILP
Aghalari et al. (2021)	✓	✓		✓			MILP
Bąk and Zalewski (2021)	✓			✓			PM
Zhu et al. (2021)							
Bhurtyal et al. (2024)		✓	✓	✓	✓	✓	2-SOP
Binsfeld et al. (2024)		✓		✓	✓		BMIP
Van der Plas (2024)			✓	✓	✓	✓	MCDA
Bedoya-Maya et al. (2025)	✓			✓			DES
This study	✓	✓	✓	✓	✓	✓	MILP

* ILP: Integer Linear Programming; MINLP: Mixed Integer Nonlinear Programming ;
MILP: Mixed Integer Linear Programming; PM: Polish Method of water channel design;
2-SOP: two-stage stochastic optimization; BMIP: Biobjective Mixed Integer Programming;
MCDA: Multi-Criteria Decision Analysis; DES: Discrete Event Simulation

As shown in Table F.1, previous studies have often focused on only two transport modes, with waterborne transport sometimes entirely excluded. By integrating all three primary transport modalities, and combining drought constraints and hub location selection, this study addresses a critical gap and contributes to a more comprehensive understanding of multimodal resilience under drought conditions. In addition, this research allows for both the establishment of new hubs and the expansion of existing terminals, enabling analysis of their respective impacts on network performance.

F.3. Data Overview

In this research, IVS (*Informatie- en Volgsysteem voor de Scheepvaart*) is used, which is provided by Rijkswaterstaat. This data includes all vessels passing Lobith between 1 January 2014 and 9 March 2025, the transported weight and vessel capacity, vessel characteristics (length, beam and draught), origin and destination, and type of cargo. Open source data on the river discharge at Lobith in the same time period was derived from Rijkswaterstaat as well. Water levels on the gauge stations of Druten, Lobith, Duisburg, Köln, Kaub, Maxau, and Basel were derived from Rijkswaterstaat and Elwis.

Data analysis revealed how the loading factor changes when river discharge drops. This showed that using shipments of an average day would overestimate the amount of cargo being transported. From the data, the list of shipments has been derived from a day where the river discharge was around the

Agreed Low River discharge level.

F.4. Network and Problem Description

This research considers a multi-modal multi-echelon location and routing problem. The first echelon involves waterborne transport from Rotterdam to a terminal or hub located along the Rhine river where cargo is transshipped to road or rail transport. Terminals and hubs are transshipment locations where echelons meet. Both have the exact same function: facilitating modal shift. However, terminals refer to existing terminals and hubs to potential new locations. The second echelon includes the flow of trucks and trains from the terminals and hubs to the final destination. In terminals and hubs, cargo can also be reloaded to waterborne transport (shallower draught vessels M6, M4 and M2), which is still part of the first echelon.

The admissible edges differ by transport modality and per vessel type. All vessel types start from the origin and sail to a terminal or hub. In a terminal or hub, cargo can be unloaded. This cargo can be loaded onto shallower draught vessels (M6, M4, M2) to sail further over the Rhine river to a terminal or hub further upstream. From there, or directly in the first terminal or hub of transshipment, the cargo can be reloaded onto road or rail transport to head directly to the final destination. Cargo is not allowed to be transshipped to another M8 vessel in a terminal or hub other than Rotterdam. Cargo cannot reach the final destination by other transport modalities other than road or rail. Lastly, cargo can only reach its final destination by rail if the terminal or hub in which the cargo was transshipped has access to rail infrastructure.

The problem is modeled on a directed graph $G(N,E)$ where N represents the set of nodes and E is the set of arcs. N includes the set of terminals T, including the subset of potential new hubs (H), the subset of existing terminals that can be extended (P) and the set of origins (O) and destinations (D). $N = N_1 \cup N_2$ includes the set of nodes in the first echelon (N_1), and second echelon (N_2). The set $N_1 = O \cup T$ includes the origin (O) and the transshipment terminals. The set $N_2 = T \cup D$ includes the set of terminals, including the potential new hubs, the terminals that can be extended and the final destinations (D). $E = \{(i,j) | i,j \in N, i \neq j, (i,j) \in A \cup B \cup C\}$. A holds for M8 vessels departing from the origin to a transshipment terminal along the Rhine river. B holds for shallower draught vessels M2, M4, and M6, but not Large Rhine vessel. C holds for transport by train and truck, where transport by train is only possible if node i has access to rail infrastructure. Figure F.1 illustrates the graph of the problem.

$$A = \{(i,j) | i \in O, j \in T\}$$
$$B_1 = \{(i,j) | i \in O, j \in T\}, B_2 = \{(i,j) | i \in T, j \in T\}$$
$$C = \{(i,j) | i \in T, j \in D\}$$

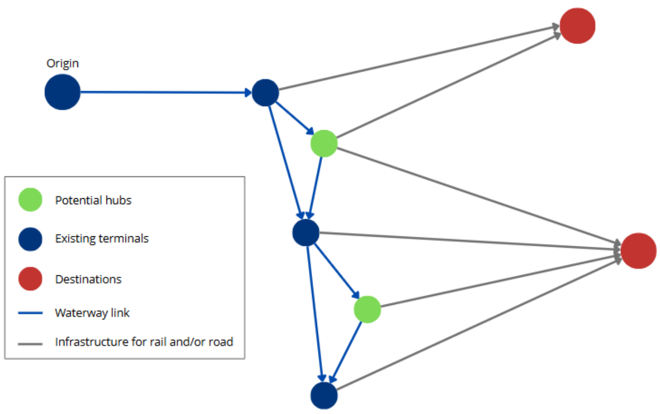

Figure F.1: Graph of the problem.

The distances of all arcs are Euclidean distances. The waterway edges have a maximum draught that affects the effective loading capacity of the different vessel types on a link.

F.5. Model Formulation

Shipments have to be shipped from the origin to the destination. Actual data of the shipments are measured at Lobith. Therefore, the cargo has to depart from the origin by waterborne transport. The cargo of each shipment has to arrive at the corresponding destination, but can be split over different transport modalities along the route. When cargo is being transshipped, the shipment tag and destination of the cargo should be preserved. If cargo is being transported by waterborne transport, the vessel's draught cannot exceed the available draught. The cargo carried by a vehicle cannot exceed the vehicle capacity, and cargo transshipped in a terminal or hub cannot exceed the terminal capacity. If a terminal is selected for extension, the original terminal cannot be used, and only if a hub is selected for establishment or a terminal is selected for extension, cargo can flow through it. There are some potential hub locations with multiple size options, where at most one of the size options for the same location can be selected. This also holds for the extension of terminals if multiple sizes are available.

F.5.1. Model Assumptions and Simplifications

- The river discharge as measured at Lobith is equal over the whole Rhine river.
- Only vessels of type M2, M4, M6, and M8 are included in the model.
- Tarnsshipments to a shallower draught vessel are allowed. Shipments cannot be consolidated.
- Transport is based on transported weight.
- The final destinations are labeled to rail yards. Last-mile transport from yard to the actual destination is not considered. Trucks also drive to the rail yard.
- Establishment and extension costs vary based on the size of establishment. Storage costs are not considered.
- Transport is simulated from a holistic perspective, only focuses on port-hinterland transport, simulates in drought conditions only, and does not simulate in time steps.

F.5.2. Mathematical Formulation

In this section a mathematical model of this problem is proposed. The notations that will be used in this paper are shown in Table F.2.

The loading on a vessel is limited by the available draught. The available draught ($draught_{ij}^{max}$) is based on Equation F.1. The guaranteed depth and equivalent water level are determined by CCNR (n.d.).

$$\text{Available draught} = \text{guaranteed depth} + \text{actual level} - \text{equivalent level} - \text{under keel clearance} \quad \text{(F.1)}$$

Dropping river discharge levels result in dropping actual water levels and thus decreasing available draught in a river section. All vessels have an empty draught ($draught_{empty}^{k}$) and a loaded draught ($draught_{loaded}^{k}$). All vessels have their own transport capacity. The loading factor, which is the ratio of the actual load to the vehicle capacity, of a vessel has a linear relationship with the vessel draught ($draught_{vessel}^{k}$. The vessel draught cannot exceed the available draught because of the risk of grounding. From this, the effective capacity can be computed as shown in Equation F.5.

$$draught_{\text{vessel}}^{k,\text{LF}} = draught_{\text{empty}}^{k} + draught_{\text{diff}}^{k} \cdot LF \quad \text{(F.2)}$$

$$draught_{\text{vessel}}^{k,\text{LF}} \leq draught_{ij}^{max} \quad \text{(F.3)}$$

$$LF_{\text{max},ij}^{k} = \min\{1, \frac{draught_{ij}^{max} - draught_{\text{empty}}^{k}}{draught_{\text{diff}}^{k}}\} \quad \text{(F.4)}$$

$$cap_{\text{eff}}^{kij} = cap_{k} \cdot LF_{\text{max},ij}^{k} \quad \text{(F.5)}$$

Table F.2: Sets and indices, decision variables and parameters of the hub selection formulation.

Sets and indices		
F	Set of shipments that have to be send from the origin to the destination	
$O \subset T \subset N$	Origin (Rotterdam, node 1)	
$N1 \subset T \subset N$	CTU Tiel (node 2)	
$D \subset N$	Set of destinations where d_f is the destination d of shipment f	
T	Set of all terminals along the Rhine river that allow for modality shift of containerized transport	
$H \subset T \subset N$	All potential hub locations (16 options) along the Rhine river There are 3 locations for potential new hubs that have multiple size options: $H_1 \subset H$ = hub options for Homberg location $H_2 \subset H$ = hub options for Koblenz Raptors location $H_3 \subset H$ = hub options for shunting yard location	
$P \subset T \subset N$	Existing terminals of which the size can be extended There is one terminal that can be extended with different sizes: $P_1 \subset P$ = extending options for terminal BCTN Nijmegen	
N	Set of nodes, $i, j \in N$ i represents forward node, j represents backward node	
K	Set of transportation modes. $k, l \in K$ (1 = M8 vessel, 2 = M6 vessel, 3 = M4 vessel, 4 = M2 vessel, 5 = train, 6 = truck)	
V_k	Set of vehicles of modality k. $v_k \in V_k$	
E	Set of admissible edges (i, j) in E	
Decision variables		**Unit**
$z_{ij}^{fd_fkv_k}$	weight cargo of transshipment f for destination d_f transported by vehicle v_k of mode k from node i to j	Ton
$d_t^{fd_fkv_k}$	vehicle specific change in weight of cargo of shipment f for destination d_f shifted from vehicle v_k of mode k in terminal t	Ton
S_t	1 if terminal t is selected for extension/establishment, 0 otherwise	{0,1}
$\delta_{fd_f}^{v_k}$	1 if vehicle v_k of modality k is used for shipment f to destination d_f	{0,1}
Parameters		**Unit**
FC_k	Fixed vehicle costs for using a vehicle of modality k	EUR/vehicle
C_k	Transport costs per ton-km using transport modality k	EUR/ton-km
CE_t	Time equivalent terminal establishment/extension costs of terminal $t \in H \cup P$	EUR/day
d_{ij}^k	Distance between node i and node j using mode k	Kilometer
CT_k	Costs per hour to (un)load cargo of modality k	EUR/hour
$d_{\text{abs},t}^{fd_fkv_k}$	absolute value of vehicle specific change in weight of cargo of shipment f for destination d_f shifted from vehicle v_k of mode k in terminal t	Ton
cap_k	Vehicle capacity of mode k	Ton/trip
cap_t	Daily handling capacity of container terminal t (or potential hub h or extended terminal p which are subsets of T)	Ton/day
$q_{v_k}^{fd_f}$	Initial loading of shipment f for destination d_f transported weight by vehicle v_k	Ton
$draught_{ij}^{max}$	Maximum draught from node i to j	m
$draught_{empty}^{k}$	Empty draught of modality k for $k \in \{1, 2, 3, 4\}$	m
$draught_{\text{vessel}}^{k,\text{LF}}$	Vessel draught of vessel type $k \in \{1, 2, 3, 4\}$ given the loading factor LF	m
$draught_{diff}^{k}$	Difference in empty and loaded draught for modality k for $k \in \{1, 2, 3, 4\}$	m
$LF_{\max,ij}^{k}$	Maximum loading factor of transport mode $k \in 1, 2, 3, 4$ (vessel types only) on arc i, j given the available draught	-
cap_{eff}^{kij}	Effective capacity of modality $k \in 1, 2, 3, 4$ (vessel types only) on arc i, j given the available draught	Ton
v_{load}	Loading rate of a container crane	Ton/hour
RC	Available capacity of the rail freight network	Ton
$H_{\max}$	Maximum number of new hubs h to be established	-
$P_{\max}$	Maximum number of existing terminals p that can be extended	-
ϵ	Small value to activate arc flow	-
M	Big M, large value	-

The mathematical formulation can be formulated as follows:

$$\min Z = \sum_{f\in F}\sum_{k\in K}\sum_{v_k\in V_k} FC_k \delta^{v_k}_{fd_f} + \tag{F.6}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V}\sum_{(i,j)\in E} z^{fd_fkv_k}_{ij} c^k d^k_{ij} +$$

$$\frac{\sum_{f\in F}\sum_{d_f\in D}\sum_{k=1}^{4}\sum_{v_k\in V}\sum_{t\in T\setminus\{O\}} d^{fd_fkv_k}_{abs,t} CT_k}{v_{\text{load}}} + \sum_{f\in F}\sum_{d_f\in D}\sum_{k=5}^{6}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in D} \frac{z^{fd_fkv_k}_{ij} CT_k}{v_{\text{load}}} +$$

$$\sum_{t\in H\cup P} CE_t S_t$$

Subject to

$$z^{fd_fkv_k}_{ij} = q^{fd_f}_{v_k}, \forall f \in F, d_f \in D, k \in \{1,2,3,4\}, v_k \in V, i \in O, j \in N1 \tag{F.7}$$

$$\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T} z^{fd_fkv_k}_{ij} = q^{fd_f}_{v_k}, \forall f \in F, d_f = j, k \in \{5,6\}, v_k \in V, j \in D \tag{F.8}$$

$$\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in T\setminus\{O\}} z^{fd_fkv_k}_{ij} = \sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in T\setminus\{O\}} z^{fd_fkv_k}_{ji}, \forall f \in F, d_f \in D \tag{F.9}$$

$$d^{fd_fkv_k}_{t} = z^{fd_fkv_k}_{it} - z^{fd_fkv_k}_{tj}, \forall f \in F, d \in D, k \in \{1,2,3,4\}, v_k \in V, t \in T, (i,t) \in E \tag{F.10}$$

$$\text{Where: } d^{fd_fkv_k}_{\text{abs},t} \geq -d^{fd_fkv_k}_{t} \text{ and } d^{fd_fkv_k}_{\text{abs},t} \geq d^{fd_fkv_k}_{t} \tag{F.11}$$

$$\sum_{f\in F} \delta^{v_k}_{fd_f} = 1, \forall v_k \in V, d_f \in D \tag{F.12}$$

$$z^{fdkv_k}_{ij} = 0, \forall f \in F, d \in D \setminus \{d_f\}, k \in K, v \in V_k, (i,j) \in E \tag{F.13}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V} d^{fd_fkv_k}_{\text{abs},t} \leq \text{cap}_t, \forall t \in T \setminus \{H \cup P\} \tag{F.14}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V} d^{fd_fkv_k}_{\text{abs},t} \leq \text{cap}_t S_t, \forall t \in H \cup P \tag{F.15}$$

$$\sum_{i\in T}\sum_{j\in D}\sum_{f\in F}\sum_{v_k\in V} z^{fdkv_k}_{ij} \leq RC, \forall k = 5, d_f = j \tag{F.16}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{j\in H\cup P} z^{fd_fkv_k}_{ij} \leq MS_t, \forall t = j \tag{F.17}$$

$$\sum_{f\in F}\sum_{d_f\in D}\sum_{k\in K}\sum_{v_k\in V}\sum_{i\in T}\sum_{t\in P} z^{fd_fkv_k}_{ij} \leq M(1 - S_t), \forall j = t \in T \tag{F.18}$$

$$z^{fd_fkv_k}_{ij} \leq cap_k LF^k_{\max,ij}, \forall f \in F, d_f \in D, k \in \{1,2,3,4\}, v_k \in V, (i,j) \in E \tag{F.19}$$

$$\sum_{h\in H} S_h \leq H_{\max} \tag{F.20}$$

$$\sum_{h\in P} S_h \leq P_{\max} \sum_{t\in H_1} S_t \leq 1 \tag{F.21}$$

$$\sum_{t\in H_2} S_t \leq 1 \tag{F.22}$$

$$\sum_{t\in H_3} S_t \leq 1 \tag{F.23}$$

$$\sum_{t\in P_1} S_t \leq 1 \tag{F.24}$$

$$S_t \in \{0,1\}, \forall t \in H \cup P \tag{F.25}$$

$$\delta_{fd_f}^{v_k} \in \{0,1\}, \forall v_k \in V, f \in F, d_f \in D \tag{F.26}$$

$$z_{ij}^{fd_fkv_k} \geq 0, \forall f \in F, d_f \in D, k \in K, v_k \in V, (i,j) \in E \tag{F.27}$$

$$d_{\text{abs},t}^{fd_fkv_k} \geq 0, \forall f \in F, d_f \in D, k \in K, v_k \in V, t \in T \tag{F.28}$$

The model aims to minimize the sum of the total vehicle fixed costs, the variable transport costs, the costs for transshipment and the daily hub establishment costs, as shown in **??**. This optimization is subject to a set of constraints. Equation F.7 ensures that all the shipments are sent into the network in Rotterdam with the vessel as defined in the shipments. Equation F.8 ensures that all cargo of all shipments arrives in the correct destination. Equation F.9 ensures flow conservation of the shipments in the intermediate nodes. Equation F.10 ensures tracking of the transshipments in the terminals, where Equation F.11 shows the linearization of the absolute value of transshipment tracking. Equation F.12 ensures that each vehicle can only carry one shipment for one destination. Equation F.13 ensures that the destination of the shipment cannot change by not allowing for flow if the destination is not the destination of the cargo. Equation F.14 and Equation F.15 ensure that the capacity of the terminals and hubs is not exceeded. Equation F.16 limits the cargo transported by rail. Equation F.17 allows flow via the hub if the hub is selected. Equation F.18 ensures that if a terminal is selected for extension, the original terminal cannot be used anymore because the extended terminal has to be used. Equation F.19 ensures that the flow on a vessel does not exceed the effective capacity to make sure the available draught is not exceeded. Equation F.20 and **??** can limit the amount of terminals to be selected if the cargo has to be routed through the existing terminals only. Equation F.21, Equation F.22, Equation F.23, and Equation F.24 ensure that at most one hub for establishment or terminal for extension can be selected if there are multiple size options to choose from on a certain location. Equation F.25 and Equation F.26 ensure the binary domains of the variables S_t and $\delta_{fd_f}^{v_k}$. Equation F.27 and Equation F.28 ensure non-negativity of $z_{ij}^{fd_fkv_k}$ and $d_{\text{abs},t}^{fd_fkv_k}$.

The model is implemented in Python and a Gurobi solver is used to find the optimal solution of the minimized costs.

F.5.3. Results Base Model

The base model simulates transport of the shipments when the river discharge is 1400 m^3/s and based on the existing terminals only. The base model is used for model verification and is a benchmark for comparing the scenarios with decreased river discharge, while keeping all other factors constant, to analyze the impact of lowering river discharge on the Rhine river transport system.

The total costs for transporting the shipments at normal river discharge is €1.021 million. These total costs consist of 46.2% fixed vehicle costs, 51.5% of variable transport costs, and 2.3% of transshipment costs.

Table F.3 shows the terminals used for transshipment, the corresponding utilization of the terminal capacity, the weight that is shifted to road and rail, and the final destinations of the cargo handled in the terminals. From the terminals selected, there is only one with access to rail infrastructure. The final destinations of the shipments shifted to rail, are located relatively far from this terminal. This indicates that, to make rail transport economically viable, the distance of shipments shifted to rail needs to exceed the break-even threshold. The total shift to rail in the base model is used to define the available rail capacity for the scenarios, which will be elaborated in section F.6. In all other terminals, the shipments are shifted to road transport to the final destination.

Table F.3: Transferred weight in the selected terminals and the corresponding terminal utilization when the river discharge at Lobith is 1400 m^3/s.

Terminal	Terminal utilization	Shift to road	Shift to rail	Destinations
BCTN Nijmegen	22.7%	2760.1 ton	-	Oberhausen, Seelze
Contargo Emmerich	14.5 %	-	1767.0 ton	Seelze, Basel
Nordfrost Wesel	100%	6086.9 ton	-	Oberhausen
UCT Dormagen	32.1%	1955.0 ton	-	Hagen, Köln
Contargo Ginsheim	68.8%	4190.0 ton	-	Mannheim, Basel

For the performance of the transport modalities, the total performance of all vessel types is 72% of the total transport performance. The transport performance of trucks and trains are about equal with 1,180 thousand ton-kilometers. These transport performances result in 258 thousand kilograms CO_2-equivalent emissions of the transport of the cargo.

F.5.4. Model Verification

To verify correct working of the model, some manual checks have been performed. The flow continuity is verified. The shipments arrive completely at the right destinations. The model makes the right decisions for cost minimization by selecting the cheapest transport option given the distance threshold for a certain flow. Terminal capacities are not exceeded. Only if a hub is selected for establishment or a terminal is selected for extension, cargo flows through it. For this, hub selection and terminal extension were allowed in the base model as well. At most one size option was selected if a hub or terminal for extension included multiple size options.

F.5.5. Sensitivity Analysis

A sensitivity analysis has been performed on the base model by varying all cost parameters, and the capacities of trains and trucks and the crane rate ranging from -50% to +50%. The sensitivity analysis depends on the way the shipments are formulated with the initial vessel type, loading and final destinations of the shipments. The results of the sensitivity analysis can be found in Appendix 1.

The model is most sensitive to the truck-related parameters. This is because a lot of trucks are used for transport to the final destinations. Increasing the fixed costs or the variable costs for trucks by 50% results in a total cost increase of 7%. The model is most sensitive to a reduction in the variable transport costs of trucks, which is a result of the high transport performance of trucks and the fact that transport by truck is most expensive. Transport from the terminals to the finals destinations is highly dependent on road transport.

F.6. Scenario-based Analysis

In the future, the river discharge levels are expected to decrease. For 2050, the expected Agreed Low River discharge level is expected to be 800 m^3/s (Van der Mark, 2022). In 2100, the river low river discharge levels can be more extreme with 650 m^3/s (Van der Mark, 2022). In the future, the available rail capacity is also uncertain. If political priorities focus on passenger rail transport, the available rail capacity can decrease. However, in light of the European Green Deal, it is also possible that the rail infrastructure is expanded to increase the available rail capacity. Based on this, Table F.4 shows the scenarios as defined for this research.

Table F.4: Overview of the scenarios with the corresponding water discharge level and the rail freight capacity.

Scenario	Name	Water discharge level	Rail freight capacity
1	*Current ALR*	1020	Normal
2	*Regression*	800	Low
3	*Stagnation*	800	Normal
4	*Adaptation*	800	High
5	*Crisis*	650	Low
6	*Disruption*	650	Normal
7	*Maximizing sustainable shift*	650	High

F.6.1. Network Design

From all the potential hubs and terminals that can be extended, a network design has to be selected. Optimization of the different scenarios with allowing for the establishment of hubs and expansion terminals, resulted in a top 3 hubs that were selected in each scenario. One of these hubs had access to rail infrastructure, the other two had only access to the road network. One of the hubs with road access was only used for some transshipments. When selecting the two hubs with the highest capacity utilization, the total costs increased with 8.5%.

If a budget were included that was slightly below the total hub establishment costs, the rail terminal would not be selected and the total costs would increase with 2.2%. However, because no terminal with access to rail is available in the region of Nijmegen, it was chosen to analyze the impact of the rail terminal and the hub with road access that had the highest terminal utilization. From a cost minimization point of view, the model did not select to expand existing terminals. This indicates that the available capacity of the currently existing terminals does not strictly limit the cargo that has to be transshipped in the network.

F.6.2. Results Scenario-based Analysis

In this section, the results of the scenarios are provided. Each scenario represents a system with a future river discharge level and a certain available rail capacity. For each scenario, the total costs and the total CO_2-equivalent emissions of the transport are analyzed.

Figure F.2 shows the total costs in each scenario. The analysis reveals that the costs rise when river discharge decreases and all other factors remain constant. The total cost increases by up to 6.7% for each step decrease in river discharge. The analysis also indicates that the establishment of hubs leads to a decrease in total cost of up to 3.6% compared to the system with only existing terminals. Figure F.3 shows the transport performance of each modality in each scenario. From this comparison, it is shown that the establishment of hubs allows for increased transport performances of most of the vessel types and trains in each scenario, while the performance of trucks decreases with the establishment of hubs. This means that, with the establishment of hubs, more cargo can be transported by waterborne transport over greater distances. Additionally, the establishment of hubs as selected in the network design allows more cargo to be transported by rail over greater distances.

The results indicate the value of adding a hub with rail access in the region of Nijmegen, for the destinations that are located further from the terminals before Kaub. In terms of cost minimization, the flow transported by train has to exceed distance thresholds to make rail transport economically viable. The establishment of hubs increases the transport performance of most vessel types. As a result, the total CO_2-equivalent emissions of the transport reduce with hub establishment. If the river discharge becomes extremely low to sail past the main bottleneck of Kaub, establishment of a terminal with rail access still contributes to reducing the total cost and CO_2-equivalent emissions of the transport.

Lastly, increasing the available rail capacity also contributes to a slight reduction of 0.4% of the total costs, when other factors remain constant. When keeping the river discharge constant, an increase in the available rail capacity in combination with hub establishment contributes best to the total utilization of the available rail capacity.

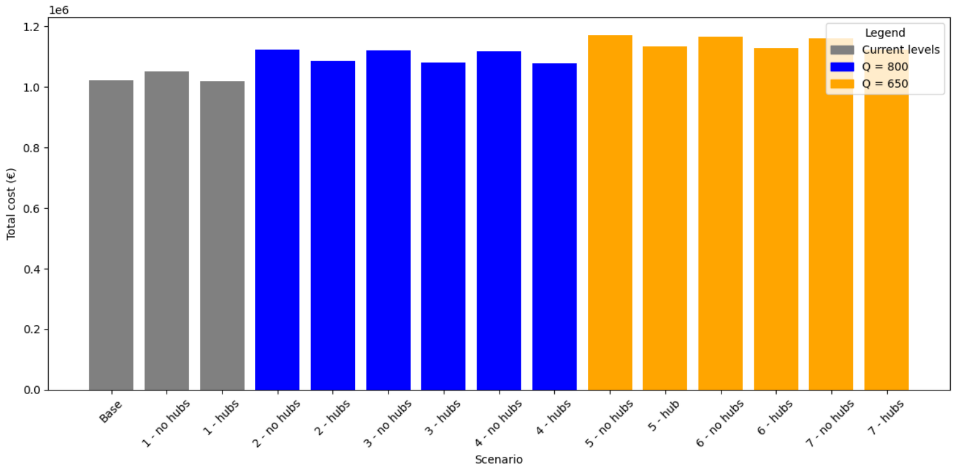

Figure F.2: Overview of the total costs for each scenario with and without hub establishment. Grey is for the base model and the current Agreed Low River discharge. Blue is for the predicted low river discharge of 2050. Orange is for the predicted low river discharge of 2100.

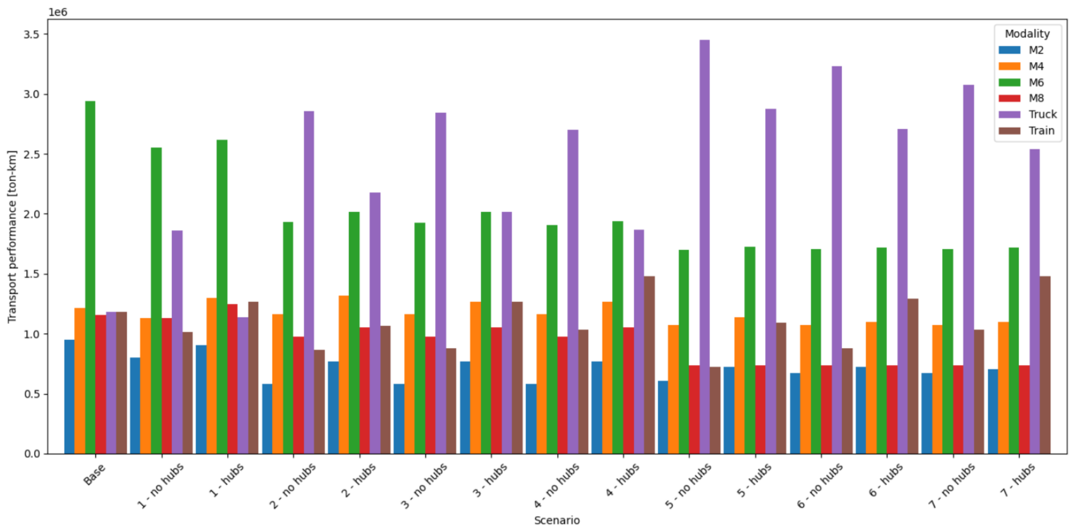

Figure F.3: Overview of the transport performance of each transport modality in each scenario with and without establishment of hubs.

In conclusion, the results suggest that strategic establishment of hub locations to facilitate modal shift in response to low water levels has the potential to enhance the drought resilience of the port-hinterland transportation system of the Rhine river. The advantages can be increased with the expansion of the existing rail capacity. The advantages include a reduction in the total cost for transportation, a decrease in CO_2-equivalent emissions of the transport, and a reduction in the transport performances of trucks also relieves the congested road network.

F.7. Discussion

The analysis results reveal the benefits of hub establishment in response to lowering water levels. Strategic establishment of hubs to facilitate modal shift on the Rhine river led to a reduction of around 40.000 euros (3.6%) of the transport of 1 day. Without the establishment of hubs, lowering water levels affect the daily total costs by up to 6.7% for each step decrease (from 1400 to 1020, 1020 to 800, and 800 to 650 m^3/s). The new hubs increase the transport performance by waterborne transport and rail because of the different allocation of shipments to terminals for transshipment. This not only reduces the total costs, but also reduces the CO_2-equivalent emissions of the transport. Increasing the available rail capacity reduces the total costs slightly (0.4%) but is more beneficial in combination with the establishment of a hub with rail access. The sensitivity analysis revealed the critical dependence of the transport by truck, regardless of the rail capacity.

While this study focused on the Rhine river, the model applies to to other port-hinterland systems. The challenges confronted by the port-hinterland system of the Rhine river, low water levels, high carbon emissions of transport, and congested networks, mirror issues which are encountered by different port-hinterland systems as climate changes. The advantages of the establishment of hubs in response to low water levels show that this is a promising strategy to enhance climate resilience.

The findings of this study imply that the inland waterway system can become more resilient against low water levels as a result of climate change. The establishment of hubs results in increased transport performance of vessels and trains, and, therefore, reduces the total costs and CO_2-equivalent emissions and relieves congested road networks. The location of hubs, accessibility to rail infrastructure, and the capacity of a new hub are all related to each other and have to be considered together when selecting what hubs to establish. For terminals with access to rail infrastructure, it only makes sense if the final destination of the shipments transshipped to rail exceeds certain distance thresholds. Expansion of the rail infrastructure contributes slightly to cost reduction, but is more beneficial when a hub with rail access is established. Policymakers are encouraged to incentivize the establishment of new hubs to improve the climate resilience of the port-hinterland system, aligning with the European Green Deal. Although the system is highly dependent on road transport, reducing truck-related costs is counterproductive to reaching the goals of the European Green Deal. These provide insights for policymakers on the trade-offs of where and what hubs to establish to increase the reliability of the inland waterway system in terms of lowering water levels.

F.8. Conclusion

The objective of this research is to enhance the drought resilience of the port-hinterland container transport over the Rhine river from Rotterdam to the German hinterland by strategic establishment of hubs to facilitate modality shift. By doing so, the research aims to give insights in the impact of strategic location planning of new hubs along the Rhine river to facilitate modal shifts.

Without hubs, transport costs increase by up to 6.7% for each step decrease in river discharge. Hub establishment increases the transport performance of vessel types and, therefore, reduces total daily transport costs by up to 3.6% and lowers CO_2-equivalent emissions by enabling more efficient use of waterborne and rail transport while reducing truck reliance.

Rail-connected hubs, particularly near Nijmegen, prove most effective when the distance by rail exceeds the break-even threshold to make rail transport economically viable. This is strongly linked to the allocations of shipments to terminals for transshipments. While increasing rail capacity alone yields a limited benefit on cost reduction (0.4%), its impact grows when combined with hub development. Even under extreme low discharge, hubs with rail access continue to improve cost and emission performance.

F.8.1. Limitations and future research

Although this study offers meaningful insights for trade-offs on the establishment of hubs to increase the drought resilience of the Rhine river from a holistic, cost minimization perspective, it is essential to address the limitations. When developing the model, several assumptions and simplifications were made.The model only focused on port-hinterland transport. This was corrected by allocating a part of the terminal capacity to the import. In the real system, transport is two directional. Additionally, the model only considers the effects of hub establishment in low river discharge periods. The model did not simulate in time steps. Therefore, the assumption had to be made that trucks and trains are unlimited available in the terminals and hubs. This is not realistic and therefore the capacity of the rail transport was limited based on the transshipments to rail at normal river discharge levels. Simulation in time steps would allow for including the arrival of trains in terminals and requires inventory tracking of containers in the terminals. This would also allow for including storage capacity.

Regarding the limitations, further research is required. It is recommended to perform further research on model improvements to gain better insights in the impact of the establishment of the terminals, also in non-drought periods. These improvements include two-directional transport, simulation in time steps, including more vessel types, increasing transport demand, and using river discharge predictions based on climate projections as input. This research investigated climate resilience in terms of the available draught. Further research can also focus on bottlenecks in terms of the width of the fairway, which is also affected by low water levels. Solutions such as longitudinal dams narrow the fairways further, allowing other bottlenecks to emerge.

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Appendix 1.

Table 5: Sensitivity analysis with parameter values and percentage change of the total costs.

Parameter	Parameter values							Percentage changes (%)					
	-50%	-25%	-10%	Base	+10%	+25%	+50%	-50	-25	-10	+10	+25	+50
FC M2	1300.00	1950.00	2340.00	2600.00	2860.00	3250.00	3900.00	-1.15	-0.58	-0.23	0.23	0.58	1.15
FC M4	1587.50	2381.25	2857.50	3175.00	3492.50	3968.75	4762.50	-1.56	-0.78	-0.31	0.31	0.78	1.56
FC M6	4110.00	6165.00	7398.00	8220.00	9042.00	10275.00	12330.00	-2.83	-1.42	-0.57	0.57	1.42	2.83
FC M8	10900.00	16350.00	19620.00	21800.00	23980.00	27250.00	32700.00	-7.51	-3.75	-1.50	1.50	3.75	7.51
FC truck	87.26	130.89	157.07	174.52	191.97	218.15	261.78	-7.33	-3.67	-1.47	1.47	3.67	7.33
FC train	5788.50	8682.75	10419.30	11577.00	12734.70	14471.25	17365.50	-2.85	-1.42	-0.57	0.57	1.31	2.26
C M2	0.046	0.069	0.083	0.092	0.101	0.115	0.138	-4.50	-2.15	-0.84	0.84	1.76	2.26
C M4	0.032	0.048	0.058	0.064	0.070	0.080	0.096	-4.16	-1.91	-0.72	0.72	1.92	3.63
C M6	0.018	0.027	0.032	0.036	0.040	0.045	0.054	-5.21	-2.60	-1.16	1.16	2.61	5.18
C M8	0.013	0.019	0.023	0.025	0.028	0.031	0.038	-1.36	-0.68	-0.23	0.34	0.68	1.48
C truck	0.063	0.094	0.113	0.125	0.138	0.156	0.188	-12.91	-4.68	-1.39	1.51	3.60	7.17
C train	0.023	0.034	0.041	0.045	0.050	0.056	0.068	-2.56	-1.28	-0.47	0.58	1.27	2.46
CE t	2091.00	3136.50	3763.80	4182.00	4600.20	5227.50	6273.00	-0.21	-0.11	-0.04	0.04	0.11	0.21
CT M2	20.65	30.98	37.17	41.30	45.43	51.63	61.95	-0.10	-0.05	-0.02	0.02	0.05	0.10
CT M4	27.38	41.06	49.28	54.75	60.23	68.44	82.13	-0.13	-0.07	-0.03	0.03	0.07	0.13
CT M6	34.10	51.14	61.37	68.19	75.01	85.24	102.29	-0.64	-0.32	-0.13	0.13	0.32	0.64
CT M8	52.62	78.92	94.71	105.23	115.75	131.54	157.85	-0.18	-0.09	-0.04	0.04	0.09	0.18
CT truck	21.73	32.59	39.11	43.45	47.80	54.31	65.18	-0.15	-0.07	-0.03	0.03	0.07	0.15
CT train	231.09	346.63	415.95	462.17	508.39	577.71	693.26	-0.92	-0.46	-0.18	0.18	0.46	0.92
Cap truck	9.0	13.4	16.1	17.9	19.7	22.4	26.9	14.41	4.81	1.58	-1.36	-2.92	-4.90
Cap train	195.0	292.5	351.0	390.0	429.0	487.5	585.0	3.71	1.56	0.25	-0.44	-1.08	-0.59
v load	235	352.5	423	470	517	587.5	705	5.21	2.06	1.01	0.06	-0.46	-1.09