Drought-resilient port-hinterland connections

Investigating the impact of modality transport hubs

MSc. Thesis Civil Engineering
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Drought-resilient port-hinterland connections: Investigating the impact of modality transfer hubs

MASTER THESIS CIVIL ENGINEERING

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Preface

This thesis is written as the last part of the Master of Science in Civil Engineering, track Hydraulic Engineering, at the TU Delft. The research is carried out as part of the European project CLARION in the form of a graduation internship at the Port of Rotterdam under the supervision of the TU Delft.

I would like to thank the people of the Port of Rotterdam, and in particular Johan Gille, for their guidance and assistance during my research. It has been a wonderful experience to be part of the world's most innovative port and to collaborate with my colleagues in the Environmental Management department. I would also like to thank all parties involved in project CLARION for allowing my research to be part of the project and for facilitating helpful materials.

I would like to thank my supervisors from the TU Delft for their support and guidance during my research, especially Mark van Koningsveld and Nadia Pourmohammadzia for incorporating my research into the CLARION project, as well as Mahnam Saeednia and Fedor Baart for their prompt feedback and assistance.

I would also like to extend my gratitude to my family and girlfriend for their unwavering support throughout my studies and during this thesis. In addition, I want to thank you, my reader. I hope this report may be of use to you and that you enjoy your reading.

Luuk van der Plas
Rotterdam, Wednesday 6th November, 2024

Abstract

The transportation of goods in Europe has grown significantly due to globalization, increased trade, and improved logistics networks, with seaports playing a critical role. The Port of Rotterdam, the largest in Europe, handles substantial freight volumes, with goods flowing inland via road, rail, and waterways. However, this growth has also contributed to climate change, as the transport sector accounts for 25% of Europe's greenhouse gas emissions. Inland waterway transport (IWT), being the most sustainable mode of transport according to policymakers, is, therefore, the European Commission's favored modality for hinterland transport from seaports. This mode of transport does, however, face increasing challenges from climate change, particularly due to fluctuating water levels and more extreme weather events. The recent droughts of 2018 and 2022 have shown how vulnerable inland shipping can be when it comes to low water discharges in the European rivers and waterways. While there is a desire to increase inland shipping, the navigability of the inland waterways is getting worse in the future over the entire year due to more extreme weather conditions as a result of climate change. As a consequence, cargo owners may choose to move away from IWT towards more reliable modes of transportation. Addressing these challenges will be crucial to ensure that inland shipping can continue to serve as a sustainable transport solution in the face of climate change, and remain a reliable and affordable mode of transportation in the European supply chain network. TU Delft and Port of Rotterdam are collaborating with 20 partners on a multidisciplinary research project named CLARION, which focuses on making port infrastructure and hinterland transport more resilient and sustainable. This research will contribute to this objective.

Transporting cargo via the inland waterways from the port of Rotterdam along the Rhine-Alpine corridor is affected by low water discharges during periods of drought. Vessels are compelled to sail with less cargo to decrease buoyancy and pass navigable thresholds. These thresholds are highly affected by the low water discharges and form bottlenecks for cargo transport. These bottlenecks may be circumvented through the implementation of intermodal transshipment hubs to transship cargo from IWT to other modalities. This will ensure more efficient transport by using multiple modalities for the port-hinterland connections. This thesis investigates the potential of transport hubs to enhance the resilience of port-hinterland connections during times of low water levels, with a particular focus on the Rhine-Alpine corridor originating from the Port of Rotterdam. This research aims to quantify the impact of transport hubs to see if it is a cost-effective solution for mitigating these disruptions and maintaining efficient cargo flow throughout the entire year. Methods will be developed to reach this objective and create reusable results.

Through a literature study of previous drought periods and critical water depth thresholds, three navigable bottlenecks along the Rhine were identified at Nijmegen, Duisburg, and Kaub. Downstream of these bottlenecks, the transport hubs will be integrated and the effect of the hubs on the entire transport network will be simulated in a transport competition model. The transport model uses shortest path functions and cost functions for rail, road, and waterway from seaports towards hinterland destinations to find the cheapest seaport and modality for port-hinterland transport. Water levels are integrated into the model by assigning different available water depths to areas in the European hinterland. For these available water depths, the vessel capacity and the required number of vessel trips are determined. For the purpose of this research, only the ports of Rotterdam, Hamburg, and Antwerp are included in the simulations to check the port competition towards the hinterland, however, this can be easily extended to more ports. For each seaport, a cargo transport of 1000 TEU is simulated using the three modalities to find the cheapest option for hinterland destinations. Three different scenarios are determined to simulate in the model: a baseline scenario, a drought scenario, and a transport hub scenario, where the hubs are implemented in the drought scenario.

A data analysis, using the IVS next vessel data and water discharge data from Rijkswaterstaat, is carried out to determine the characteristics of the different scenarios and assess the reduction of cargo throughput during the drought scenario. Based on the available data, the baseline scenario reflects transport data from the past four years, and the drought scenario represents conditions during the three-month drought of 2022. It is the ambition of the CLARION project that the operability of the network remains at least at 80% during climate-based disruptions for the network to be deemed resilient, which only allows for a reduction of cargo throughput of 20%. The outcome of the data analysis shows a 54% reduction in freight transport to the German and Swiss hinterland during low water levels, which results in a necessary 43% of the baseline cargo needing to be handled at the hubs for the network to remain reliable and working at 80% operability. Assuming that transport hubs can facilitate demand during periods of drought, this translates into a necessary design capacity of 255.000 TEU annually for the three hubs combined. This capacity will be sufficient to handle the excess 43% of the baseline cargo during drought periods. For these periods, baseline vessel capacities and drought vessel capacities were determined for the hinterland destinations based on average water levels while sailing upstream on the Rhine. For each bottleneck passed, the vessel capacity is reduced and the necessary vessel trips increased. These values are integrated into the scenarios of the transport competition model along with the dimensions of the design vessel, which is taken to be an M8 Large Rhine container vessel. Only the exact locations for the hubs were added to the model as well.

A method is developed to identify suitable locations along the Rhine for the transport hubs. A Multi-Criteria Decision Making method, specifically the Best-Worst Method, was applied to create weighted criteria to rank potential locations. The expertise of professionals at the Port of Rotterdam was used to create input for the Best-Worst Method, and based on the weighted criteria, potential locations were ranked for facilitating a future transport hub. In the scope of this research, the ideal locations were found to be Noordkanaalhaven in Nijmegen, the Duisburg Gateway Terminal, and H & S Logistics in Andernach, just before Kaub. These locations were entered into the model to simulate the effect of the hubs on the transport costs for the port-hinterland connection.

The transport model was run for the different scenarios, and the most effective hub was found to be before Kaub, offering transport cost reductions if transshipment costs are kept below €50 per TEU. Duisburg proved effective during the drought scenario and for integrating rail transport during the baseline scenario. Nijmegen's hub showed less impact on creating a more cost-effective solution for IWT. Designing two terminals for 130.000 TEU annually in Duisburg and Andernach, before Kaub, would be large enough to achieve 80% operability of the baseline container transport during low water periods from Rotterdam to the German and Swiss hinterland.

In conclusion, this research delivered the method for evaluating transport hubs as a cost-effective solution against climate-based disruptions. In the case of the Rotterdam-Rhine corridor, the transport hubs can enhance port-hinterland connections and make the network more resilient against climate change. However, their cost-effectiveness depends on considering terminal handling costs, strategic placement, and integration with other transport modalities. The transport competition model proved to be useful for simulating the effect of the transport hubs on the Rotterdam-Rhine port-hinterland connection and showed to be applicable for implementation in other regions and scenarios as well. Different seaports and transport networks can be integrated along with emission calculations for different or more extensive problems. The method for analyzing the transport and water discharge data provided useful inputs for the model, which can be easily reproduced for other scenarios and locations. The location analysis can be used as a step-by-step guide for other cases to find suitable terminal locations, but it needs to be extended and improved for practical application. Using these methods, the model can provide visual representations of the transport competition, showcasing the problem of increasing low water levels and the need for a more resilient IWT network.

Contents

Nomenclature

The nomenclature provided here shows all the abbreviations used in this thesis and can be used to make reading the report easier

Abbreviation	Definition
BWM	Best-Worst Method
CLARION	Climate Resilient Port Infrastructure
FEU	Forty feet Equivalent Unit
IWT	Inland Waterway Transport
MCDM	Multi-Criteria Decision Making
TEU	Twenty feet Equivalent Unit
NUTS	Nomenclature of Territorial Units for Statistics
ukc	under keel clearance

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Introduction

1.1. Research Context

The transportation of people and goods is increasing worldwide. This is due to globalization, increased available resources, and expanding trade. The integration of European markets and the development of advanced logistics networks have made it easier for goods to flow efficiently across borders. With growing demand for consumer goods, industrial products, and raw materials, the transport sector, including road, rail, inland waterways, and maritime shipping, has seen substantial expansion. This growth has emphasized improving infrastructure, enhancing sustainability, and addressing capacity challenges in key transport corridors across the continent. Different transport modes and corridors are in constant competition when it comes to costs, speed, and accessibility. The most advantageous mode of transport will create the most demand and will become the most desirable in the network. A key component in this global transport network is seaports, between which the largest freight transport occurs. 67.9% of the total freight transport in the EU is maritime transport and roughly 2% inland waterway transport (Eurostat, 2023). The port of Rotterdam, the largest seaport in Europe, handles freight transshipments totaling no less than 439 million tonnes. This makes it a vital factor in European and global freight transport, from which cargo is imported into Europe and sent inland via roads, rail, and inland waterways. To show the increase in freight transport in the Netherlands over the past 25 years, data from CBS, 2023, is shown in Figure 1.1 where light blue shows inland transport, dark blue imports, and green exports. However, the rise in transport also contributes significantly to climate change. The transport sector is one of Europe's largest sources of greenhouse gas emissions with 25% (Eurostat, 2023), particularly due to the reliance on fossil fuels. Without decisive action, these emissions are projected to increase further with a more intense impact on the environment and

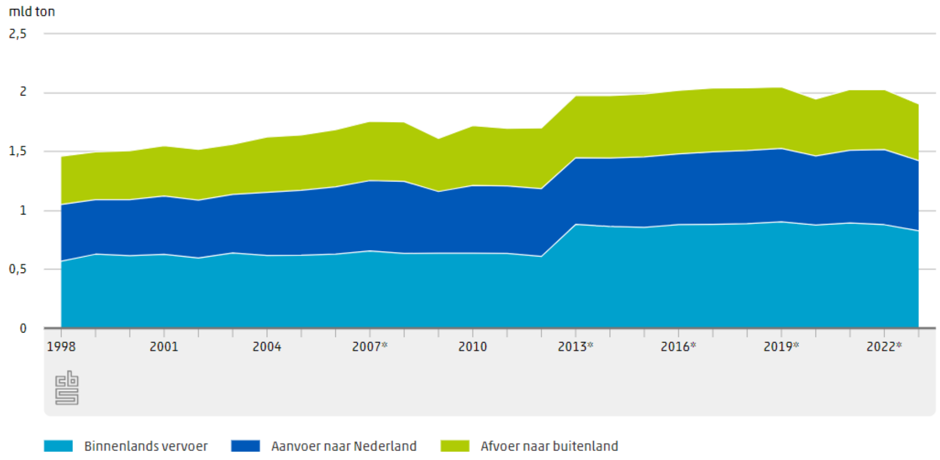


Figure 1.1: Freight transport in the Netherlands, 1998 - 2023 (CBS, 2023)

climate change. Where climate change is already showing large-scale effects on the transport network itself. Especially inland waterway transport is affected due to more fluctuating water levels. The KNMI and Klimaatadaptatie Nederland, 2023, expect the temperature to increase by 1.6 degrees by 2050 and the UCAR, 2021, state that 7% more precipitation is expected with every degree increase of global temperature. Climate change is poised to alter river discharges significantly, particularly with regard to reduced snowfall during winter. Historically, the most important waterway connected to the port of Rotterdam, the Rhine River, functioned as a rain-snow river, but with a warming climate, precipitation patterns are shifting towards rainfall dominance (Jonkeren and Rietveld, 2009). These climatic shifts are expected to have profound effects on hydrological regimes, increasing the frequency and severity of low water events while potentially leading to more intense precipitation and floods (IPCC, 2022).

In response to the pressing need for emission reduction and sustainable transportation solutions, the European Commission has outlined ambitious targets. Inland shipping, being the most sustainable mode of transport compared to road and rail, according to policymakers, is the favored modality for European freight transport (European Commission, 2021). Therefore, the Commission aims to shift 30% of road transport towards rail transport and inland shipping by 2030 and 50% by 2050 (Ambra et al., 2019). This means that with emission restrictions having bigger effects on the transport sector, inland shipping will become even more attractive (Consultancy.eu, 2024). Inland shipping for dry bulk, liquid bulk, and container cargo are already key modalities in the Netherlands and Europe, but the droughts of 2018 and 2022 have shown, however, how vulnerable inland shipping can be when it comes to low water discharges in the European rivers and waterways. During these periods, transport costs surged, and the capacity of the inland shipping network was significantly reduced. This weakened the competitive advantage of IWT, leading customers to seek alternative transport options. This demonstrates a clear desire to increase the role of inland shipping, even as navigability worsens due to more extreme weather conditions. The position of IWT in the transport market is being weakened, and a cost-effective solution is essential to prevent a modal shift away from IWT.

1.2. Research Problem

During these extreme weather conditions, periods of drought and low water levels compel inland vessels to transport less cargo and sail more frequently. During periods of high water levels, waterways are restricted for sailing and limited by bridges and overpasses. This all leads to congestion along the inland waterways and ports. The reduction of the capacity of the waterways not only led to increased cost of transport but also to large economic damages in industries dependent on inland waterway transport. The road and rail networks proved unable to accommodate IWT's reduced capacity, which increased the demand for and the price of transport. Especially the German industrial hinterland areas were affected along the Rhine in 2018 and 2022, with the economic impact of the droughts even taking effect on a national level. The frequency of extreme weather events such as floods and droughts is expected to rise due to climate change (IPCC, 2022). This means solutions are necessary to prevent the system from becoming unreliable and prone to congestion. The inland shipping sector needs to become more resilient against these events if it wants to stay a solid form of transportation over the entire year and, by doing so, prevent a modal shift towards rail and road transport.

Periods of drought tend to have a larger impact on the IWT than floods, as they last for longer periods of time (Scheurle, 2011). Low water discharges significantly reduce the cargo capacity of vessels, undermining the cost-effectiveness and emission advantages of inland shipping per cargo unit transported (Caris et al., 2014). As a result, the sustainable advantage of inland shipping is jeopardized by the challenges posed by fluctuating water levels and the increased frequency of low water events. The cargo transport over the last 8 years over the Rhine is shown in Figure 1.2. The figure shows the impact of the large droughts in 2018 and 2022 on the total transported cargo this year. It shows the slow reduction of freight transport over the Rhine each year, while the aim of the European Commission is to increase transport via inland waterways.

Panteia has brought out an investigation that shows a reduction in inland container transport (Schuttevaer, 2024). The total freight volume in the Netherlands has reduced by 5%, from 301 million tonnes to 286 million tonnes, and the overall reliability of inland shipping has decreased (Quist, 2024). Jonkeren, 2020, also states in a research that the share of IWT in the modal split will decline between 2030 and 2050. The increase in cost and transport time is hurting the business case of IWT, and the favored position of

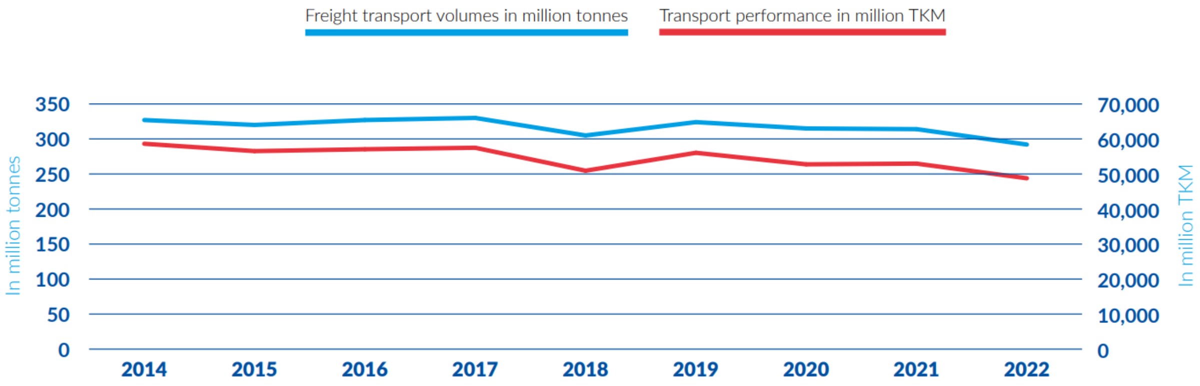


Figure 1.2: Total inland waterway freight transport reduction over the last 10 years. CCNR analysis based on Destatis and Rijkswaterstaat, 2023, transport performance (CCNR, 2023b)

IWT in transport competition is being reduced. This is why a cost-effective or time-effective solution is necessary to naturally bring transport business to it. IWT for dry bulk is also significantly affected by the low water levels, even more than container transport, due to the higher density of the transported cargo (Kievits, 2019). The draught of vessels carrying dry bulk is greater than that of container vessels, requiring more reduction to the transported cargo to maintain a reasonable draught at low water levels. In addition to transport capacity, there is a restriction on the number of barges a push convoy can transport simultaneously, further reducing transport capacity. The 6-barge convoys are not allowed to sail on the Rhine with a water discharge lower than $1000\text{m}^3/\text{s}$, which means that the largest barge available can't sail, and this cargo needs to be handled by other vessels. Furthermore, there are logistical limitations at low water levels, such as sailing restrictions, time windows, reduced speeds, and an increase of terminal waiting times to the increased number of barges arriving (van Dorsser, 2015).

The cargo throughput is most hindered by certain navigable bottlenecks. Bottlenecks are locations along the waterway network where low water levels occur most frequently. These are the locations in the hinterland where the sailing depth is the lowest, limiting the loading rate of the vessel for the entire trip. The loading capacity for vessels sailing over the river is determined by the lowest point on this trip, where no exception is made for the trip, even if this location significantly reduces the loading capacity. The cost for transport and the height of potential low water surcharges applied to IWT depend on these loading capacities and water depths at these bottlenecks. While previous research has already delved into various aspects of inland shipping at low water levels, extensive research is still necessary, especially in mitigating low-water disruptions. The effects and disruptions caused by low water periods are still very significant when considering the economic impact of the recent droughts. Other mitigations and measures need to be taken to decrease the negative effects of these events.

TU Delft is collaborating with 20 partners on a multidisciplinary research project named CLARION, which focuses on making port infrastructure and hinterland transport more resilient and sustainable. The research problem is that the extended effects of climate change on the inland shipping sector have not been fully researched, particularly regarding the effects of fluctuating water levels and extreme weather events. Therefore, project CLARION was created to improve the resilience of European ports against climate change and make the sector more sustainable (Port of Antwerp Bruges, 2024). Objectives and means of verification are formulated within the project to quantify the resilience of the network. Three means of verification are considered in this research, with the first one being the most important due to the measurability of this objective in existing data and by use of the transport model:

- Ensure resilience of infrastructure of connected inland waterways infrastructure and connected hinterland land infrastructure to extreme weather events by assuring at least 80% operability during the disruptions.
- reduce environmental impacts >20%.
- Contribute with at least 20% increase in modal shift of port hinterland connections towards zero- and low-emission transport systems.

The consequences of climate change are occurring sooner and more frequently than expected, and this thesis aims to help make port-hinterland connections more resilient.

1.3. Research Gap

The European transport networks function as a complex system where demand and supply balance each other out through competitiveness between modalities, ports, and terminals. The recent drought periods have shown that this network can be easily disrupted and have large economic consequences (Fechner and Luman, 2023 & Stratelligence, 2021). The research gap for this problem is that possible mitigation measures have not yet been fully researched, and solutions are necessary to strengthen the position of IWT during harsher climate conditions. Solving the entire problem of resilience against climate change is too extensive for the scope of this research, so the focus is on one possible solution: modality transport hubs before bottlenecks to optimize inland waterway transport during low water discharges. A potential solution that is proposed more often in research based on climate change and water levels but has not completely been researched yet (Riquelme-Solar et al., 2015). More often, other solutions were investigated, like vessel modifications, waterway modifications, or more efficient port operations (NOVIMOVE, 2024), but integrating transport modality hubs into the competitive transport network hasn't been investigated yet. These hubs function as inland terminals and can combat reduced shipping during low water levels by using multi-modal transport for the same connections. This could prevent the reduction of capacity of the IWT network by using a more efficient combination of different modalities as hubs and spokes (Zheng and Yang, 2016). The main mean of verification that is used to quantify the improved resilience of this solution is the 80% operability objective, also used in project CLARION.

Although transport modality hubs are already used in the inland waterway network to bundle cargo, they are not yet integrated to combat periods of drought and create a more efficient hub-and-spoke network during low water levels and reduced vessel capacities. Connections from the seaport to the hinterland, which use only one modality for transport without transshipment, are not altered for these low water periods. The possible positive effects of the implications of transport modality hubs have yet to be investigated during these periods. Models are available based on port competition, modality competition, or reduced capacity of inland vessels due to low water levels, but not where these three factors come together and are integrated into one model. This model will be created with and without the implementation of transport hubs to show the competition of the port-hinterland network for different water levels and how the hubs will influence this competition. This will investigate the research gap in the effect of transport hubs during low water periods and will develop a method for quantifying the effect of transport hubs on a designated transport network.

1.4. Research Objective

The objective of this research is to create a method to quantify the impact of transport hubs on port-hinterland competition during periods of drought. By doing so, it aims to provide a practical solution that can be implemented to maintain efficiency and reliability in the face of climate-induced challenges. This focuses on using the transport hub as a cost-effective solution for transporting goods from the seaport to hinterland regions in the port-hinterland competition network. A model is created that can simulate the cargo transport network between the seaports and hinterland areas, where the favored seaport and modality are found for different destinations. Other perspectives were also possible, like decreasing delays and congestion in the network or increasing terminal operations from the operator's point of view. The importance of transport competition and the search for the most advantageous mode of transport is highlighted here to provide a method to determine the cost-effectiveness of the transport hubs.

1.5. Research Scope

The main focus will be on the use of transport hubs and modality changes before navigable bottlenecks to optimize inland waterway transport costs during low water discharges and prevent transport reduction and congestion in the hinterland of the Port of Rotterdam. The scope of this research will be the waterways and the transport networks connected to the Port of Rotterdam, mainly the Rhine-Alpine corridor. The Rhine-Alpine corridor handles the highest cargo volumes in the hinterland of the Port of

Rotterdam and is heavily affected by periods of drought and low water levels. The Port of Hamburg and the Port of Antwerp-Bruges will also be taken into account due to the competitive business case of the three ports in the northwestern part of Europe. Inland waterway transport costs will be compared with road and rail transport from the three ports to determine the cheapest option to transport cargo to a NUTS region in the hinterland. The transport hubs will be integrated to check for improvement in the Rotterdam-hinterland connection and to identify more efficient rerouting solutions using multi-modal transport. Only road, rail, and inland waterway transport coming from seaports are considered in port-hinterland competition, where other options like freight transport via air or inland rail transport from the east are left out. The European waterway network is visible in Figure 1.3, showing the large network of waterways available for IWT. Other European ports and waterways can eventually make use of the same method to check their competitive advantage during periods of average water levels and low water levels.

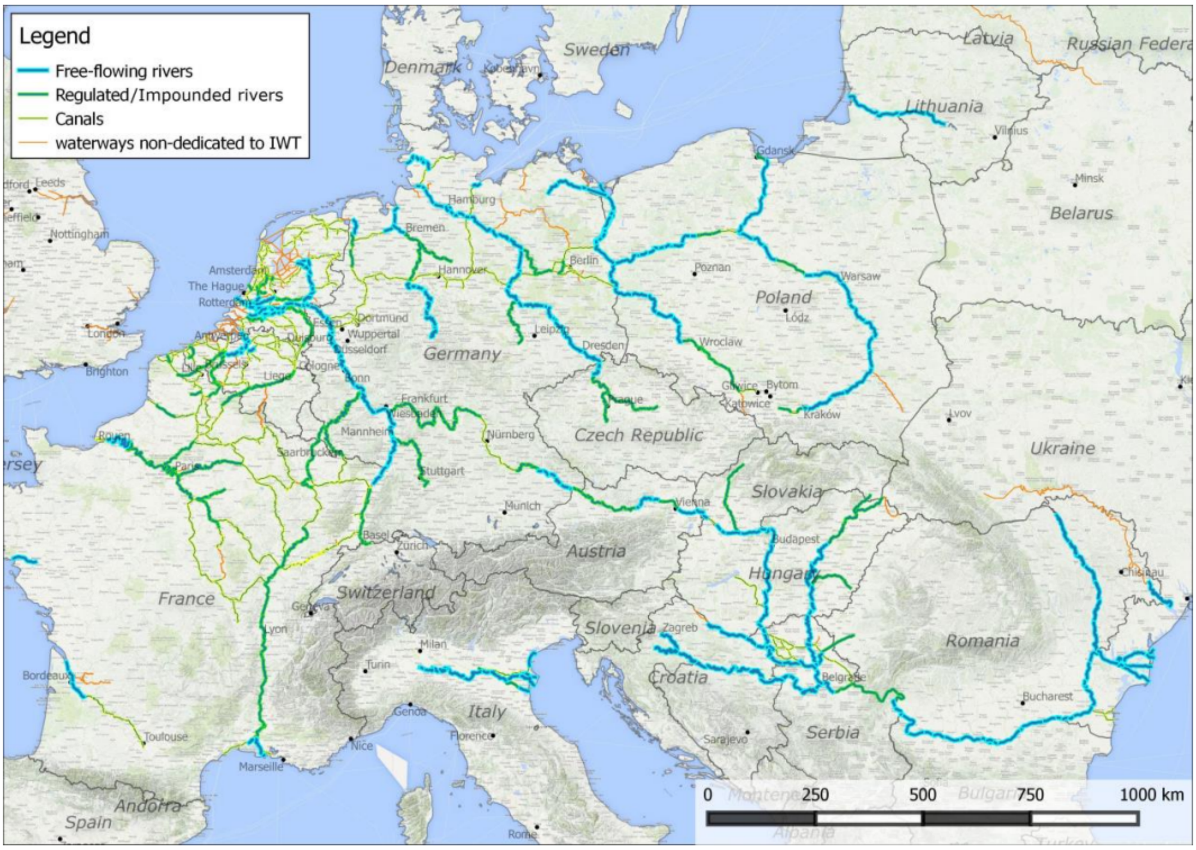


Figure 1.3: Inland waterway network for European cargo transport (Source: STC-NESTRA based on UNECE information, Markus and Robert, 2017)

1.6. Actor analysis and societal relevance

In this research, these stakeholders are considered which are involved in the IWT business and are impacted by the recent droughts. For these stakeholders, the interests considering IWT and the impacts of the droughts and potential hubs are considered. This will indicate how potential transport hubs will be received and how these will potentially affect their business and day-to-day lives. The main stakeholders for freight transportation over the Rhine are:

1. Port of Rotterdam - as the main origin or destination for hinterland transport
2. Shipping companies and other transport companies
3. Large industry in the hinterland of the Rhine
4. Rijkswaterstaat - who is responsible for the navigability of the river

5. The EU - who supports sustainable transport
6. Nature organizations
7. Local residents

Most stakeholders benefit from a reliable Rhine corridor if it is for economic or environmental reasons, except for the local residents, who could be hindered by increased IWT. A larger portion of the freight transport through Europe that is carried out over water will save money and reduce emissions when compared to road and rail transport. As an ethical reflection of the potential outcome of this research, the first and second-order impacts of the implementation of transport hubs are defined per major stakeholder. Their main values are looked at, and how these values impact this research. The outputs are shown in Table 1.1

Actor	First order impact	Second order impact	Values	Impact on research
1	Improved hinterland transport at low water levels	Port of Rotterdam proven reliable for future transport, economical revenue	economical growth, reliability of transport network, sustainability	driven to find a feasible and cost-efficient solution
2	different shipping routes to transport hubs	More reliability on all year transport, less influence of spot-market	economic security, livelihood security	as few impact on existing transport as possible
3	resources arriving with fewer delays, less risk of stopping work	more certainty for the future, expand possibilities and good competitive position	low transportation costs, reliable transportation	determine boundary conditions, cost efficiency
4	new inland ports in shipping traffic, more responsibilities arise due to new transport hubs	fewer major interventions are required to keep transport going in the dry season	keeping the Netherlands safe and dry, sustainable environment, ensure transport runs smoothly	Sustainable solutions, don't disrupt daily transport
5	Smooth transport through Europe in dry season	More transport directed towards IWT, fewer emissions	sustainable environment, smooth continental trade and transport	Look at solutions beneficial to the entire continent
6	new constructions disrupting habitats	sustainable IWT more attractive, fewer emissions due to transport	protect the environment, protect animal habitats, strive towards a sustainable future	Opt for the sustainable solution, limit construction, limit nature impact
7	noise pollution from the construction	job opportunities, increased traffic in the area	keep peace and quiet in the area, quality of life does not deteriorate	Keep the impact on local residents as low as possible

Table 1.1: Actor analysis

The enormous trade and freight transport mentioned in Figure 1.2 brings with it economic and societal impact. The first and second-order impacts are shown for the main stakeholders in Table 1.1, but this research also has an impact on society. Adverse societal impacts are considered like:

- Construction along riverbanks
- Traffic congestion around new transport hubs
- Investment costs to realize these new inland ports

The low water levels and recent droughts cause the transport to come to a halt and economies to get hurt. The 2018 drought led to a decrease in the industrial production of 1.5% in Germany, which already caused a decline of 0.4% of the economic output (Fechner and Luman, 2023). Ministerie van infrastructuur en waterstaat, 2022, state that the added value of the transport industry in the Netherlands in 2019 was €34,7 billion. The economic damages of the 2018 drought to the transport industry amounted to 400 million euros in the Netherlands. The annual costs of drought were already determined to be 67 million annually on transport before the last severe droughts (Stratelligence, 2021). This underscores the importance of a reliable and robust inland waterway transport network for the entire Dutch society. This sector is key to the economic growth of the Netherlands, and any redirection of transport towards other networks will have widespread effects.

Enhancing the sustainability and resilience of the entire inland waterway transport (IWT) sector is crucial for the broader society in Europe. Transport hubs represent one potential solution to address this pressing issue. Despite the costs and challenges associated with establishing hubs, these can be offset by the potential economic benefits and future growth opportunities of the IWT network.

1.7. Research Questions

The objective of this research is to answer the main research question:

> How can transport hubs be evaluated as cost-effective solutions along the Rhine corridor to make the Port-hinterland connection more resilient against climate change?

With the sub-questions designed to help answer the main research question:

1. Which locations form critical bottlenecks for inland shipping on the Rhine, and what are the average delays and added transport costs due to the increase of necessary vessels?
2. How can we model port-hinterland transport competition for different seaports and modalities, and how can transport hubs be implemented into this model?
3. How much cargo must be relocated on another modality at the hub locations to guarantee the reliability of the hinterland shipping network for a critical low water level?
4. How to identify suitable locations along the Rhine for transport hubs, considering existing infrastructure and accessibility to other transport modalities?
5. How will these modality changes at the transport hubs affect the total transport costs of the cargo compared to one modality transport for the same destination?

1.8. Research Method

This thesis is designed as an analytical study combined with a modeling cycle, allowing for a comprehensive analysis of transport dynamics and the integration of various transport modalities. First, a literature study will be conducted to determine the state of the art and useful methods for this research, providing a foundation for identifying variables and gaps in existing studies. Research based on inland shipping with low water levels, combined with studies focused on the last mile principle and transshipment, will be used to develop knowledge on the subject and identify the research gap.

Recent droughts in 2018 and 2022 will be examined using historical transport data and water level records to identify navigable bottlenecks for inland waterway transport and consequently answer the first research question. The critical bottlenecks found will be checked for increased transport costs and delays during periods of low water levels.

Existing models will be used as guidelines or as a base for a Python-based transport model where hubs and modality shifts are integrated. This will answer the second research question and represent a transport competition model. The main input variables of the model will be a scenario of water levels along the waterways of the Rhine based on historical drought data and a certain number of TEUs to be transported. The main output will be the price per cargo shipment to be transported to the designated location. The transport hubs will need to improve the cost of freight transport per shipment or come close to one modality pricing to become cost-efficient.

Transport-volume data from recent years will be used as input for the model and will undergo a data analysis. This will address the third research question, for which the reduction of cargo throughput around the different transport hubs is analyzed. Other information, like vessel fleet compositions and water levels, will provide input that can be used in the transport model. This will be done based on two different modeling scenarios: a baseline scenario, a drought scenario, and a drought scenario where transport hubs can be integrated.

Potential locations for transport hubs before these bottlenecks will be identified using a location analysis and Multi-Criteria Decision Making method. Using this method, potential locations are graded and ranked based on their characteristics, which, in the end, will give an answer to the fourth research question. After the determined hub locations and scenario characteristics are entered into the transport model, results are retrieved for the baseline, drought, and transport hub scenarios. A capacity indication of the transport hub will be made to complete the business case for integrating transport hubs to battle low water levels. Using this approach will also consider the potential economic and environmental impacts of implementing such hubs.

1.9. Research Structure

This research aims to give an understanding of the implementation of transport hubs in inland waterways and how they can be used to increase the resilience and reliability of the transport network at low water levels. Shortcomings can be identified when it comes to costs and necessary infrastructure for the transport hubs. Existing methods and relevant literature are investigated in chapter 2. The location of the bottlenecks is derived in chapter 3 along with the rest of the Methodology for answering the other sub-questions. The method for creating a transport competition model is explained in chapter 4. The answer to the third question is retrieved by executing a data analysis in chapter 5 on the available transport data. And the method used to find suitable locations is explained in chapter 6. With the information and inputs from chapter 5 and chapter 6, the transport model is set up, which will answer the fifth research question by providing results for each scenario. The model results will be presented in chapter 7 and discussed in chapter 8. At last, the conclusion and recommendations are written in chapter 9. The report outline is also visible in Figure 1.4.

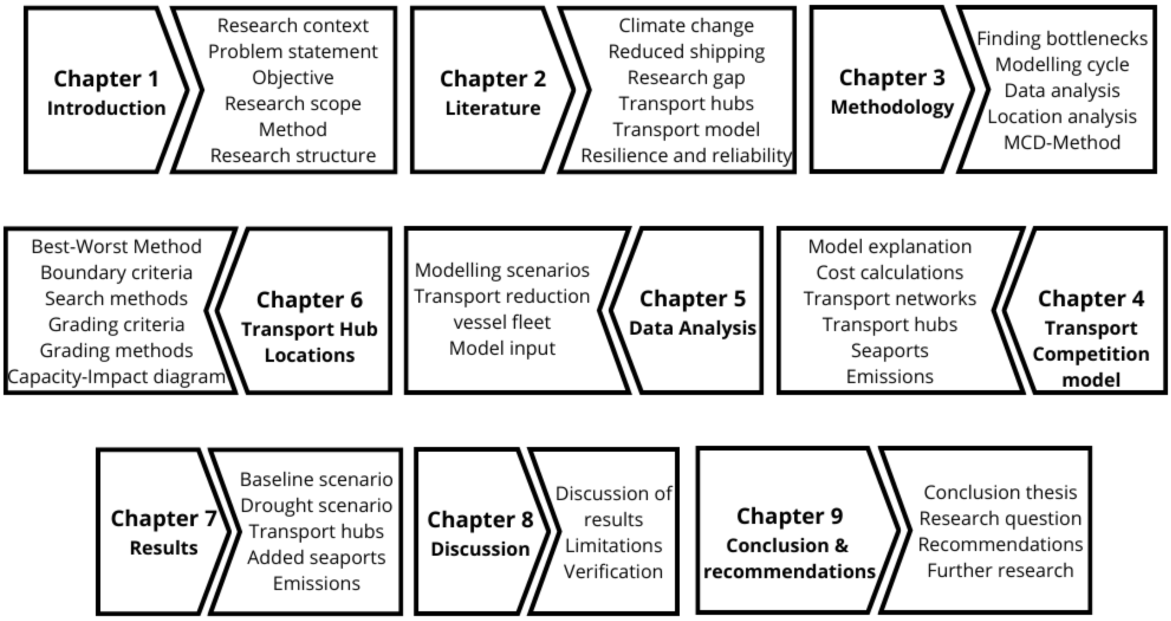


Figure 1.4: Report Outline

2

Literature review

The literature review aims to explore relevant topics within the subject of inland shipping affected by low water levels, with the objective of identifying relevant research to contribute to this master's thesis. Studies and papers on the subject will be looked at to identify the research gap when it comes to using transport hubs for inland waterway transport and to gain knowledge in the research already done by professionals and experts in similar subjects. The scope of this topic needs to contain a research of approximately 21 weeks and, therefore, shouldn't be too broad or too narrow to ensure feasibility and relevance. Due to the many aspects involved in this topic and the many solutions to be investigated, restrictions on the scope are important.

2.1. Climate resilient port-hinterland connections

Climate change and extreme weather events have formed problems for inland shipping for a long time and this research aims to fill a gap in the available literature for mitigating these problems. Different aspects of the inland waterway transport network are considered to find a potential solution that improves the waterway network's resilience against climate change. The IWT network works as a complex system and therefore the available literature and researched methods have been thoroughly examined. The impact of climate change on inland shipping has been known for quite some time and has already been described 15 years ago by Jonkeren and Rietveld, 2009, and J. C. Van Meijeren and Groen, 2010. These and other earlier studies underscored the potential implications of climate variability and change on water levels, navigability, and overall operational efficiency within inland waterway systems. Periods of drought tend to have a larger impact on the IWT than floods, as they last for longer periods of time (Scheurle, 2011). Low water discharges significantly reduce the cargo capacity of vessels, undermining the cost-effectiveness and emission advantages of inland shipping per cargo unit transported (Caris et al., 2014). As a result, the sustainable advantage of inland shipping is jeopardized by the challenges posed by fluctuating water levels and the increased frequency of low water events. Existing research on navigability during low water levels is looked at and considered to find a possible research gap. Riquelme-Solar et al., 2015 investigated the increased frequency and length of low water periods and proposed strategies to mitigate the impacts of the drought. Increased storage capacity, vessel modifications, waterway modifications, and mixed transport were proposed.

2.1.1. Mitigation methods for reduced IWT during low water levels

The European project, NOVIMOVE, 2024, was designed to investigate inefficiencies in the seaport-inland logistics chain with respect to port logistics and varying water levels. Here was dived into the design of the vessels (Friedhoff, 2020), limiting draught, the port terminal times by implementing mobile terminals(Ramne and Alias, 2024), dynamic scheduling at locks and bridges, improved load factor of container vessels, improved river navigation, and new business models.

Vinke et al., 2022, propose an integral method for a model that links the state of the river to supply chain performance, while their subsequent study Vinke et al., 2023, tells a lot about vessel deployment under different water discharges on the Rhine river. It's a recent study that shows efficient vessel fleet composition during drought periods could improve the capacity and resilience of the network. Hekkenberg, 2015 explained in research for ideal vessel sizes that water discharges and vessel capacities should be combined in the same research. Gobert and Rudolf, 2023 looked at the actors involved and showed that for multiple solutions, intermodal organizations appear significant, and the network would benefit from a coalition of Rhine ports and intermodal organizations. Caris et al., 2014, explain the opportunities of integrating inland waterway transport into the intermodal supply chain where it mentions that models that integrate intermodal transport decisions with supply chain decisions need research attention. M. Zhang, 2013 investigated the network and found that CO2 taxes and transshipment hubs would be the best solutions for creating a more integral transport network in Europe.

2.1.2. Gap in existing methods for mitigating reduced IWT

Investigating the literature on mitigating the effects of low water levels on IWT, multiple improvements have already been investigated, like adjusting the waterway or the vessel design. One method that stands out for the beneficial potential that hasn't been implemented to improve IWT during low water levels is intermodal transport. Different reports suggest the potential of mixed transport and integral intermodal transport to benefit the port-hinterland supply chain. This hub and spokes concept can be further investigated to see if it has a beneficial effect on the reduced capacity of the IWT network. The importance of a model where different water discharges and vessel capacities come together is also mentioned. Following the proposed strategies from Riquelme-Solar et al., 2015 and looking at the existing research, mixed transport during low water periods is the least investigated strategy to improve the resilience of the transport network.

2.2. Hubs and spokes concept, and inter-modal transport

The potential solution further investigated revolves around the utilization of transport hubs for inland shipping during low water levels at bottlenecks within the Rhine corridor, aimed at enhancing Port-hinterland connections and increasing resilience against extreme weather events. The focus on transport hubs aims to streamline inland waterway operations and minimize the impact of disruptions on the efficiency and reliability of the network by implementing the hub and spoke model. The importance of efficient container hubs between shipping and road transport is explained by Li et al., 2022, where they proposed the idea of physical internet. The positive effect of modal shifts on the last mile and combining water and road transport is explained by Pourmohammad-Zia and van Koningsveld, 2024. Y. Zhang et al., 2020, show that the use of transshipment terminals reduces the cost for barge companies (up to 14%).

2.2.1. Hub and spoke concept

The hub and spoke concept is a distribution network where the hub sits in the middle of the network, and origins and destinations are connected to the hub as spokes (Transvirtual, n.d.). This network is used across the world, for example, in grocery chains that use distribution centers as hubs and the different suppliers and stores as spokes. Airports could also be considered as hubs where all passengers travel from there personal spokes towards the gather at the hub. The hub and spoke concept for inland container transport turned out to be beneficial on the Yangtze by Zheng and Yang, 2016, and Zhou et al., 2023, to navigate past obstacles. Here, a tree-like structure was used, stemming from the sea port, which is also applicable to this research. The effect of the hubs on the total cost is positive but depends mainly on the operational costs of the network and, secondly, the shipping cost.

2.2.2. Inter-modal terminals

Further, in the hinterland along the Rhine corridor, intermodal terminals are more common and are already used to transfer IWT transport towards rail modality and vice versa. A big hub for these terminals lies in the German city of Duisburg, where a lot of industry is located and is well connected to the Ruhr area. As explained by van der Geest et al., 2019, this city functions as an important location via rail transport through Europe. "In the Port of Duisburg, you can bundle sufficient volumes of freight flows and establish competitive transport concepts with optimum pre and onward carriage. In the case of combined traffic, most of the distance is covered by rail or ship to utilize the economic advantages offered by these transport methods for long distances and high freight transport capacities" (Duisport,

2024. The 2018 drought led to a decrease in the industrial production of 1.5% in Germany which already caused a decline of 0.4% of the economic output (Fechner and Luman, 2023). The German hinterland is, therefore, very dependent on inland shipping and vulnerable to climate change. Germany even underwent more economic damages when compared to the Netherlands, where the economic damages of the 2018 drought to the transport industry amounted to 400 million euros in the Netherlands. The German-Rotterdam connection will need to become more resilient against fluctuating water levels to prevent large economic losses.

2.2.3. Transshipment hubs in the Netherlands

Transshipment hubs are not new and are already used on the hinterland corridor at Alblasserdam (Maritiem Courant, 2021) and Alphen aan de Rijn (TNO, 2004) to relieve the pressure on the congested roads around the port of Rotterdam. Combining modalities at these terminals gives more transport possibilities and is operating very successfully. At both terminals, 100.000 containers are transshipped from road to water, reducing traffic on the road and reducing emissions. The terminals boost regional activity and are used to bundle road container cargo together on vessels, making the Port of Rotterdam more accessible. Other types of cargo and rail options aren't implemented at these locations, mainly because a railway line through the green heart isn't possible. These terminals are used to reduce the portion of the journey that takes place by truck. During periods of drought, a large part of the Rhine corridor remains navigable up to a certain threshold. A transport hub in this area can help link different transport modalities and thereby reduce travel time by truck.

2.2.4. Transshipment for different cargo types

Transport hubs can be used for container freight and could be possible for dry bulk, but due to transshipment restrictions and regulations, it is hard to use them for liquid bulk. Liquid bulk is usually more dangerous than dry bulk and must, therefore, be handled with more expertise (CCR and OCIMF, 2010), which requires extensive permits and large installations to store safely (BRZO, 2020). Although the vessel capacity for liquid bulk, just like dry bulk, is reduced significantly, the transshipment for liquid bulk is assumed to be too difficult for the scope of this research.

2.2.5. Reverse Modal shift

NOS, 2018, highlighted a reverse modal shift occurring that year, emphasizing the challenges faced by the road and rail sectors in accommodating part of the freight capacity of inland waterway transport during drought. As a result, congestion intensified at the container terminal within the port. Road and rail are useful alternative ways of transport, but "The problem is that the capacity of both is limited" (J. Van Meijeren and Harmsen, 2020). A hinterland transport hub would alleviate congestion at the port and would create shorter distances for last-mile road or rail transport. By implementing this solution, other modes of transportation would be better equipped to handle increased capacity in the event of disruptions to inland waterway transport. Looking at the capacity limitations of other networks, an over-designed transport hub for a large amount of cargo might be of no use. Therefore, research into other modalities is important to optimize the transport hubs as done by J. Van Meijeren and Harmsen, 2020, and by Chen et al., 2023.

2.2.6. Rail Terminal Gelderland

The province of Gelderland has previously looked into making better use of the Betuwe route by building a rail terminal at Valburg before Nijmegen (Provincie Gelderland, 2020), where cargo can be shifted from road and waterway to rail modality. Eventually, these plans failed after no contractor and operator came forward in the tender procedure for the project (Spoorpro, 2024). A research from van der Geest et al., 2019, explains that the terminal could be beneficial to relieve pressure at the port of Rotterdam and it would improve the transport potential to Italy and the middle of Europe. This is a function that is now more often performed at Duisburg or via other seaports. Still, it already shows that a potential hub at Nijmegen would be a positive addition to the transport network, even without considering the potential of increasing resilience during drought periods, which would make the hub even more beneficial.

2.3. Competitiveness in port-hinterland networks

2.3.1. Competitiveness in North-Western Europe IWT

Focusing on intermodal transport, different reports investigate how the competitiveness between modalities is handled in previous research and how multimodality is simulated. The necessity for this section is explained by Kiel et al., 2014, describing competitiveness as a vague term that needs indicators like accessibility and economic impact. Catalán et al., 2021 explains that competitiveness causes different outcomes compared to single-player outcomes, and therefore, it's important to bring in competitiveness in this research to gain more reliable outcomes. Using data from Eurostat, 2023, the main ports will be defined for this competition. The largest 3 ports will be considered for all simulations, but these ports can be extended to neighboring ports with smaller throughputs.

2.3.2. Gap in available models for competition during different water levels

Drought periods cause differences in competition towards the hinterland, a decrease in the advantage of IWT, and a change in the favored waterways from different seaports (Caris et al., 2014). Baart, 2024 is an existing model used to show port-hinterland transport at different water discharges, but where transport costs and competition of modalities aren't integrated yet. van Dorsser et al., 2020 Also created a model for sailing at different water levels, where vessel capacity can be determined. A port competition model was created by de Iongh, 2020 where the different modality costs are integrated, but water levels, emissions, and climate scenarios are still left out. All these sources combined input for a port-hinterland competition model between modalities during different water levels, but an integral solution hasn't been created for the case of port competition, low water levels, and transport hubs.

2.4. Existing models and software

Python will serve as the primary programming language for developing the proposed model, with inputs sourced from various projects hosted on GitHub. This is due to previous experience in Python and the availability of a base model applicable to this research. A similar master thesis has been done by de Iongh, 2020, which investigates the influence of sea level rise on inland shipping and port-hinterland connections. In this master thesis, the rise of sea level affecting the port location is the main research problem, but the model is helpful as a base to simulate shipping transport to the hinterland from different seaports. From this model, the shortest path functions for rail, road, and waterway transport can be used to determine the trips for all modalities. Also, the method for developing maps can be used in this report to create visual aids of the model results. Baart, 2024, has developed a digital twin for the port of Rotterdam aimed at determining vessel trips required for specific cargo volumes at varying water levels. This model can be used to determine vessel capacities at certain water levels. Route Scanner, 2024, is used in the model to determine vessel schedules and routing of freight transport through Europe and the Netherlands via IWT and rail. van Koningsveld et al., 2019, and van Koningsveld and Baart, 2020, are used for vessel capacities and extra inputs for the transport model like vessel characteristics. OpenStreetMap, 2024, is used to determine the shortest route for road transport from the port of Rotterdam and the new transport hubs. QGIS, 2021, is used to import geographical data and check for network connections in the rail and waterway networks, helpful for visualizing the transport networks and hinterland areas and finding errors in the data that cause issues for the model.

Data needs to be worked through for the model, and the right variables need to be picked out to use in the model. The data that will be used in the model will be provided by different companies and clear citations of which data comes from which source is necessary in the modeling and the documentation. Open communication will be necessary with each party involved, which data is used and when this data is used. An important aspect here is the fact that data can also be shown to other parties and not only work within a model. The main data used in the model will be the transport data over the Rhine in the past few years. For this Rijkswaterstaat, 2024a, data will be used which shows vessel trips and cargo throughputs. As mentioned earlier, the two drought years of significance are 2018 and 2022, during which significant droughts occurred. However, data from the last 10 years will be used to obtain a clear picture of steady inland shipping conditions. Important sources for this data are Rijkswaterstaat IVS data, German data from ISL, and data from the port of Rotterdam, which have tracked water levels, discharges, cargo volumes, etc., over the last decades. For determining water levels and discharges the dataset from Rijkswaterstaat, 2024b, will be used.

2.5. Quantifying resilience of transport networks

To quantify the terms reliability and resilience in this thesis, objectives and criteria must be found to test the influence of transport hubs in these two areas. Two statements of resilience are: "A general and generic property of systems, the broad ability of a system to cope with disturbances without changing state" (Angeler and Allen, 2016), "Transportation resilience is defined as the ability of a transportation system to move people around in the face of one or more major obstacles to normal function. These obstacles can include extreme weather events, major accidents, and equipment or infrastructure failures" (Ride Amigos, 2024). For this report, the disturbances are climate change-induced droughts, and the transport hubs are the method to cope with this. Angeler and Allen, 2016, also states an important aspect of over-resilience is functional redundancy, which must be watched out for when exploring new transport hub locations. Here, the thresholds are stated as the bottlenecks, and the adaptation will be dependent on whether people start using the hub in day-to-day business. Dam, 2017 explained the resilience of the network as robustness and found that interconnections for container transport between modalities have a significant on the robustness of container transport as a whole.

In the project, CLARION objectives are formulated along with means of verification. Two objectives in project CLARION which are applicable in this research are formulated as follows:

- Demonstrate technologies that increase the operational availability of port infrastructure during and after disruptions caused by climate change, natural and human-caused disruptions to 85%.
- Support the modal shift of port hinterland connections towards zero- and low-emission transport systems by 25%.

For both objectives, terms are designed in the project to establish the objectives. A few of these terms or means of verification can be achieved by implementing transport hubs in periods of drought. The means of verification where transport hubs can help achieve the goals are:

- reduce environmental impacts >20%.
- Ensure resilience of infrastructure of connected inland waterways infrastructure and connected hinterland land infrastructure to extreme weather events by assuring at least 80% operability during the disruptions.
- Contribute with at least 20% increase in modal shift of port hinterland connections towards zero- and low-emission transport systems.

The main verification method used in this report is the 80% operability during the drought period. Looking at the transport data, a value can be found for the reduced operability of the transport network and a value for the reversed modal shift during periods of drought. Other means of verification are the increased capacity of the network, reduction of reversed modal shift, and the potential reduction of emissions using the transport hubs.

2.6. Conclusion Literature review

This research will focus on the implementation of transport modality hubs to reduce climate change-based disruptions to the inland waterway transport network, mainly during long drought periods. While measures against disruptions have already been investigated and the modality hubs are already present in the transport network, the use of these hubs to increase resilience against low water levels hasn't been investigated yet. Developing a method based on a transport model that quantifies the impact of transport hubs on the port-hinterland competition during periods of drought will help to fill this research gap. Using methods for quantifying competitiveness and existing models and software to develop a transport model will help support the research objective where the transport hubs function as a measure of mitigating the disruptions caused by low water levels. This will also fill a research gap in itself. A model that incorporates competition between transport modalities and seaports isn't available yet to solve problems of low water levels. A further step-by-step explanation of these methods is given in the next Chapter.

3

Research Methodology

This research will be divided into different stages regarding the methodology. First, the critical bottlenecks are determined based on the investigative literature of the 2018 and 2022 drought. Identifying different potential bottlenecks along with the caused delays and added transport costs to answer the first research question:

Which locations form critical bottlenecks for inland shipping on the Rhine, and what are the average delays and added transport costs due to the increase of necessary vessels?

After the bottlenecks are found, the method for developing the transport model is described in section 3.2 to answer the second research question:

How can we model port-hinterland transport competition for different seaports and modalities, and how can transport hubs be implemented into this model?

In the data analysis, described in section 3.3, a method is carried out to give an answer to the third research question:

How much cargo must be relocated on another modality at the hub locations to guarantee the reliability of the hinterland shipping network for a critical low water level?

To answer this question, scenarios for the baseline and drought periods will be developed, and the cargo throughput for each scenario will be determined. The method to answer the fourth research question will be described in section 3.4 of this chapter:

Which method can be used to identify suitable locations along the Rhine for transport hubs, considering existing infrastructure and accessibility to other transport modalities?

This will be done through an MCDM method location analysis. The results of this analysis will pinpoint efficient locations for transport hubs, which will then be incorporated into the transport model. The outcomes of the data analysis will be implemented into the model as well, after which results can be retrieved from simulations to answer the last research question:

How will these modality changes at the transport hubs affect the total transport costs of the cargo compared to 1 modality transport for the same destination?

Based on all the results, the eventual necessary dimensions for the hubs will be described in the discussion. This modeling cycle will help to give an indication of the cost-effectiveness of the transport hubs. All the steps taken in this methodology are described in the flow chart shown in Figure 3.1 and will work towards a recommendation and a design for transport hubs to combat the low water levels and make the transport network more resilient to climate change. The modeling scenarios described in the flow chart are determined in section 5.1, and the other methods and analyses are explained in this Chapter. The research is divided into 3 phases, researching the necessary topics and developing the methodology for this research, working out the different methods in this research, and retrieving results from the methods and discussing the outcomes.

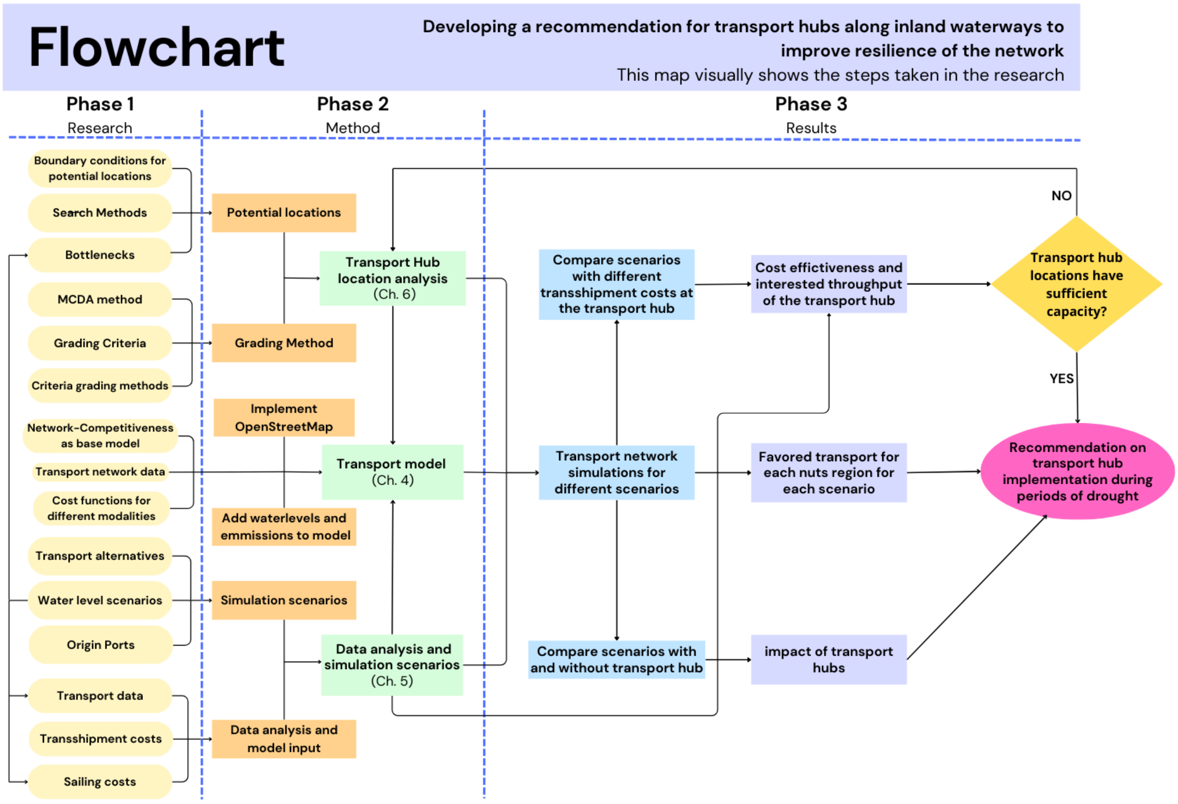


Figure 3.1: Transport hubs flow chart

3.1. Analysis of bottlenecks

As an initial step in the research and part of the methodology, potential bottlenecks along the Rhine corridor are being examined, and the main problems around these locations are being investigated to answer the first research question.

3.1.1. Pricing of IWT during low water levels

A constant problem with water levels can have different causes, and therefore each problem is being addressed separately. An important water depth is a depth where the transport obligation ceases to apply (Quist, 2024) where shipping contracts are no longer binding, and shippers shift their focus towards the spot market (Jonkeren and Rietveld, 2009). For example, the transport compensation for vessel costs increases significantly as water levels decrease. This happens from a water depth of 150 cm at Kaub, where compensation increases until the obligation ceases to apply. This happens at 80 cm at Kaub as shown in Figure 3.2 (CCNR, 2023a). At this point, shipping contracts activate a termination clause at Kaub that provides shippers with the option to dissolve the agreement and sell their transport operations on the spot market. This is where they can secure better rates compared to their standard contracts. This migration to the spot market for container transport has led to a significant surge in prices during periods of low water levels. Although stated by STC-NESTRA, 2015, that market structure in inland shipping is beneficial, extremely high prices have caused people to abandon inland shipping transport altogether, creating a reverse modal shift. For the sailing depths at different locations, so-called gauges along the side can be used, which provide the reference depth at specific locations. These reference heights can be retrieved via Rijkswaterstaat, 2024b, but aren't yet specifically expressed in the sailing depth. The relevant sailing depth can then be determined at a specific location using a rule of thumb (Binnenvaart Nederland, 2023). The rule of thumb is as follows:

$$\text{Gauge} - \text{GLW} + \text{TuGLW} - \text{ukc} = \text{sailing depth} \tag{3.1}$$

- Gauge = measured height at Gauge

- GLW = Gleichwertiger Wasserstand (Equivalent Water Level)
- TuGLW = Tiefe unter Gleichwertiger Wasserstand (Depth below Equivalent Water Level)
- ukc = under keel clearance (30 cm used)

With Equation 3.1 and the info from Rijkswaterstaat, the sailing depth for different locations and dates can be determined to identify extra bottlenecks for the Netherlands and Germany along the Rhine.

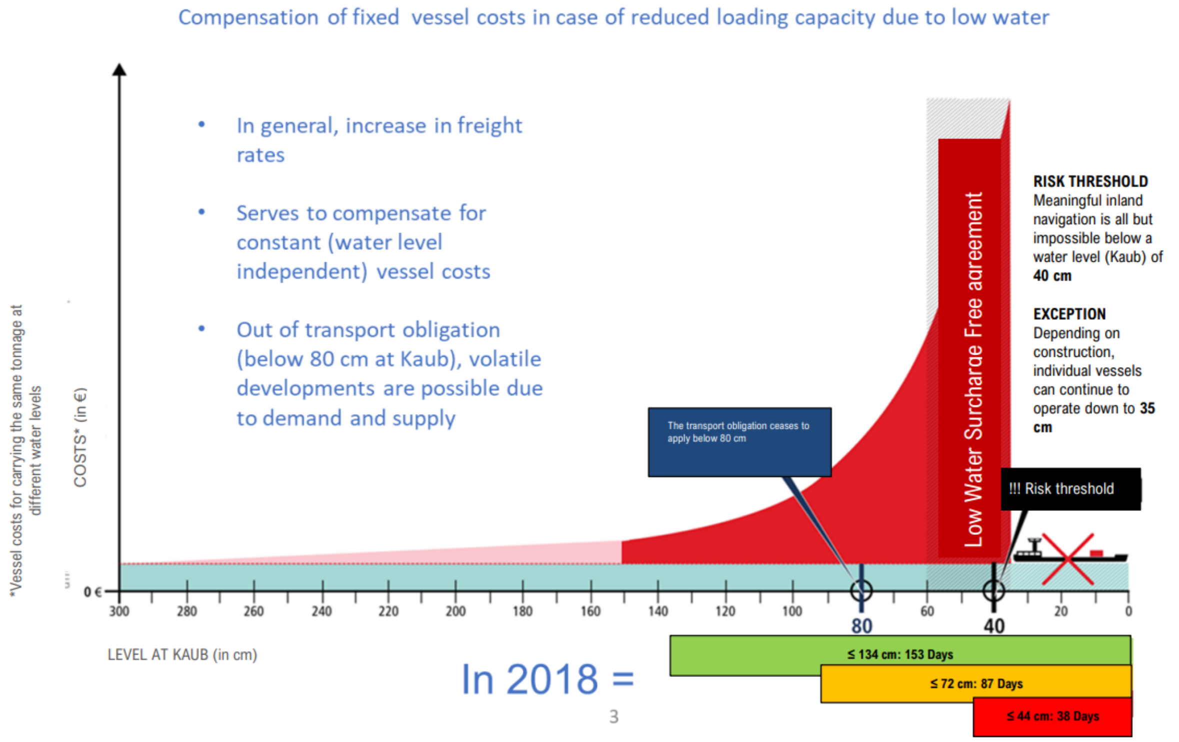


Figure 3.2: Compensation of fixed vessel costs in case of reduced loading capacity ("RHENUS logistics", 2024)

3.1.2. Low water problems at Kaub

Kaub is identified as the significant bottleneck along the Rhine in Germany by the CCNR, 2023a, where the shallow navigable channel depth along the Rhine corridor causes large disruptions at low water levels. The critical depth for Kaub is taken at 80 cm, which has big consequences if the water level stays below this water level for a longer time period. This location causes problems for the connection between the lower and upper Rhine. The upper part of the Rhine gets closed off for IWT from the lower Rhine, while the upper parts of this section are still sailable. Kara et al., 2023, state that a 30-day period of this low water level results in a 24% decrease in transported cargo. To illustrate the severity of the bottleneck, it's noteworthy that in 2018, this low-water period persisted for 80 days, while in 2022, it lasted for 37 days.

The low water surcharges determined by Contargo at Kaub are shown in Table 3.1. The water level is the level measured at 'Pegel Kaub', or gauge Kaub, and the sailing depth needs to be determined by using Equation 3.1. This data can be used to model cargo transport towards Kaub at low water levels. Contargo also maintains rates for Emmerich, Duisburg, and Cologne with each other rates found in Appendix A along with all surcharges found for the Rhine corridor. The delay at Kaub is described by Harris B.V., 1997, to increase from 0.8% to 1.2% in 2050 on a yearly basis due to low water levels. In practice, this could be a days or weeks delay during intensive droughts. These delays cause an increase in costs, trips take longer, port fees have to be paid while waiting and delays mean terminals have to make handling facilities available for longer time windows. Jonkeren and Rietveld, 2009, explain that the average maximum allowable delay time is 13%, which amounts to 3 hours for a trip taking 24 hours.

Level at Kaub Rhine km 546,3	LWZ per 20′ full	LWZ per 40′ full
150 - 131 cm	€40,00	€50,00
130 - 111 cm	€55,00	€75,00
110 - 101 cm	€75,00	€90,00
100 - 91 cm	€90,00	€145,00
90 - 81 cm	€120,00	€165,00
80 cm or below	By agreement	

Table 3.1: Low water level surcharges at Kaub (Contargo, 2024)

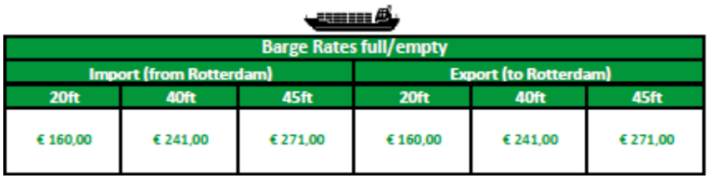
3.1.3. Bottleneck Nijmegen

Another substantial bottleneck that lies closest to the Port of Rotterdam is on the Waal at Nijmegen. Koninklijke Binnenvaart Nederland, 2023, state that the hard layer near Nijmegen, which structurally lowers the waterway, causes many difficulties. In 2018, the hard layer at Nijmegen was the lowest point sailing from Rotterdam to Duisburg, which limited vessels and barges in sailing depth(Schuttevaer, 2018). The waterway still has a deficit of about 30 centimeters after a lot of modifications have been made and the situation has already improved. Rijkswaterstaat, 2022, state that the costs due to the droughts in the Netherlands are the highest in Nijmegen, with 60 million euros annually. The location for the Railterminal Gelderland was investigated, and a suitable location was also found near Nijmegen at Valburg before the bottleneck (Provincie Gelderland, 2020). Tiel was also considered here, but although this location also forms problems during low water levels, it is close to Rotterdam and, therefore, near Nijmegen would have more impact in battling low water levels with longer sailing distances. The BCTN terminal also maintains a low water surcharge for the Nijmegen location. This amounts to €20 per TEU if the water level of the Waal falls below 2 meters.

3.1.4. Problems and opportunities in Duisburg

A third location for a potential bottleneck along the Rhine corridor is Duisburg. This is a big industrial destination for cargo originating from Rotterdam and cargo produced in the hinterland that needs to be taken to the Port of Rotterdam. This location holds a lot of infrastructure like inland terminals, industry and potential railway connections. It lies in the middle Rhine area, which is very prone to low water levels and, due to the large amount of traffic, also to congestion of cargo. The definitive bottleneck at Duisburg lies in the south, just upstream from the city and all the terminals from where barging companies charge an increase of low water surcharges (Contargo, 2024). In 2022, coal could not be supplied for power stations and the chemical industry to keep generators and factories running (VRT News, 2022). Grain could not be transported from the inland farms, and the silos were therefore overfull. The rail network, together with road traffic, turned out to be unable to cope with this problem and handle the increased cargo transport via road and rail.

The surcharge for low water levels at Duisburg is found for the Hutchinson ports in Duisburg and is calculated per 20 feet container (TEU) or 40 feet container (FEU) and is shown in Table 3.2 (Hutchison Ports, 2024). The water level is measured at ’Pegel Duisburg Rurhort’, or gauge Duisburg Rurhort, at the lower Rhine, and the surcharge starts from a water level lower than 3 meters. This data can be used to model cargo transport toward Duisburg at low water levels. Contargo also applies low water surcharges for Duisburg, which are fairly similar (slightly higher) to the surcharges required when sailing towards Hutchison ports. To compare these surcharges to the normal transport costs shown in Figure 3.3, it shows that the surcharges can be more than twice as high as the normal transport costs during periods of drought. Keeping vessel capacity higher by sailing via a transport hub can, therefore, keep the costs per cargo unit lower during periods of drought.



Barge Rates full/empty					
Import (from Rotterdam)			Export (to Rotterdam)		
20ft	40ft	45ft	20ft	40ft	45ft
€ 160,00	€ 241,00	€ 271,00	€ 160,00	€ 241,00	€ 271,00

Figure 3.3: Transport costs for container cargo between Rotterdam and Duisburg (Hutchison Ports, 2024)

Level	Between (m)		20 FT	40 FT
1	3,00	2,71	€10,00	€20,00
2	2,70	2,51	€25,00	€35,00
3	2,50	2,21	€45,00	€65,00
4	2,20	2,01	€65,00	€85,00
5	2,00	1,81	€90,00	€110,00
6	1,80	1,71	€144,00	€184,00
7	1,70	1,61	€207,00	€266,00
8	1,60	1,51	€303,00	€393,00
9	1,50	1,41	€350,00	€450,00
	Under 1,41		Upon request	Upon request

Table 3.2: Low water surcharge at Duisburg

3.1.5. Other potential bottleneck locations

The second largest bottleneck in transport costs in the Netherlands, with 11 million euros annually due to droughts, lies around Arnhem on the Neder-Rijn. However, this corridor is on a side branch of the main Rhine corridor in the hinterland of the Port of Rotterdam and, therefore, less interesting to investigate for eventual transport hubs.

Another potential location is Wesel in Germany. It lies on the intersection of 2 waterways towards Duisburg and Dortmund and, therefore, is a location passed by many vessels. Duisburg is, however, very close by with no significant navigable thresholds in between, and more infrastructure is present at Duisburg. It is also convenient that the sailing distance is longer towards Duisburg, and therefore, the IWT can be used for a longer distance.

3.1.6. Definitive IWT bottlenecks during low water levels

The three bottlenecks chosen to implement the transport hubs are chosen to be Nijmegen, Duisburg, and Kaub and are shown in Figure 3.4. For these locations, the network can be modeled with transport hubs, and a suitable location needs to be found to implement the transport hub.

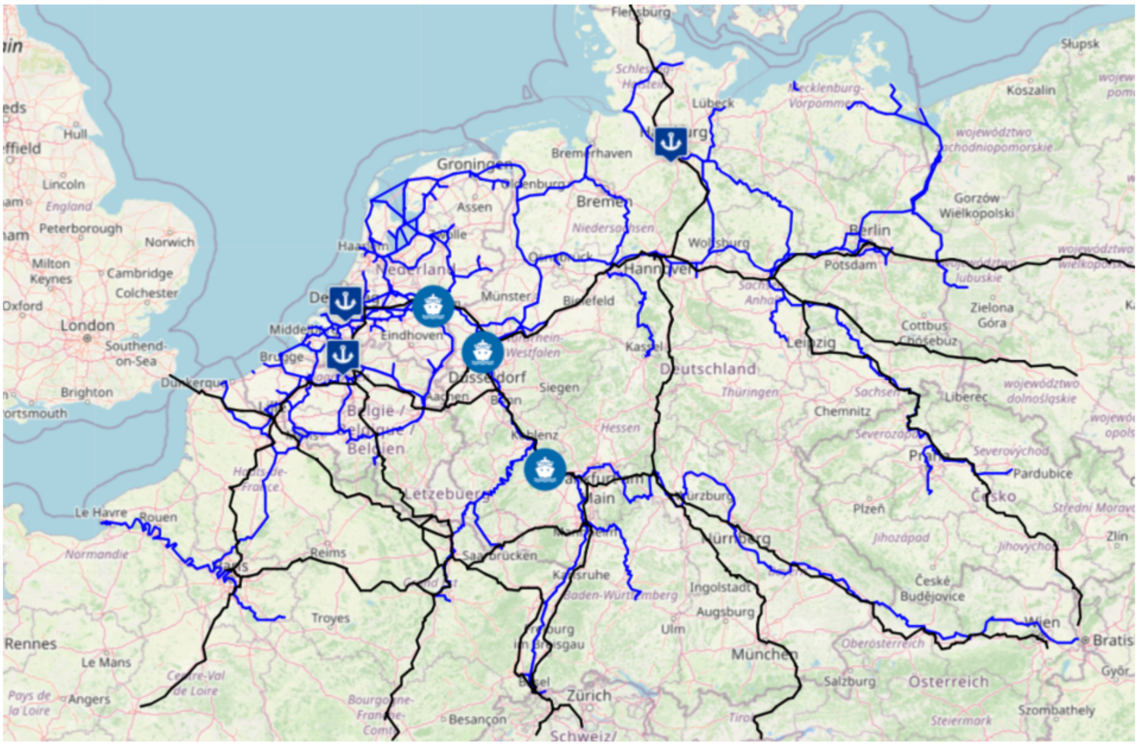


Figure 3.4: Bottleneck locations along the Rhine corridor

3.2. Methodology for transport competition model

To answer the second research question and develop an answer to the last research question and the main question, a model is developed where the competition between modalities and seaports is simulated. The transport hubs will be integrated into this competition in the baseline scenario and the drought scenario. The base for the transport model will be an old Python model developed by de Iongh, 2020, where hinterland competition is modeled for relocating the port of Rotterdam if sea level rise restructures the coastline of the Netherlands. It already features aspects of IWT and will be used as a starting point where transport hubs can be integrated. This model contains a shortest-route function, with a cost function for road, rail, and IWT, where the favored modality or port for certain hinterland transport is determined. Low water levels, extra seaports, updated transport networks, new cost functions, emissions, and OpenStreetMap, 2024, will be added to the model to simulate different scenarios considering water levels and river discharges in Europe. This will keep the shortest path functions for the three different modalities but will use a new method for calculating the transport costs for the necessary number of vessel trips. The number of necessary vessel trips will be based on the available water depth and the loading capacity of a design vessel. These water depths will be integrated based on the data analysis and the capacities of the design vessel will be determined using van Koningsveld et al., 2019, van Koningsveld and Baart, 2020, and Baart, 2024. The digital twin of the port of Rotterdam, developed by Fedor Baart, is used to determine vessel capacities at different water levels and emissions for vessel trips. It takes in discharges and vessel size to simulate trips and calculate emissions. Route Scanner will be used as an extra tool to check route schedules and hinterland connections from different ports (Route Scanner, 2024).

The model will be designed to integrate two climate scenarios: a baseline scenario, which simulates normal sailing conditions, and a drought scenario, which simulates the low water levels of recent droughts. Creating water level scenarios will be a new aspect integrated into the model, which will make the model more reliable for real-world implementation. For both scenarios, the transport model needs to find the favored seaport and mode of transport towards a hinterland NUTS region. Using this method, each hinterland region is 'won' by a seaport and a modality. For the drought scenario compared to the baseline scenario, the change in competitive advantages for the port of Rotterdam in the hinterland will be checked. After this, the transport hubs are implemented to see if 'lost' hinterland regions at low water levels can be won back from other seaports or modes of transport.

3.3. Data analysis and model input

Before developing the model, data is collected and analyzed to derive information on IWT. This will address the third research question and provide input that can be used in the transport model. It will also give insight into the necessary capacity of the hubs to keep the network operable for 80% of the baseline cargo throughput. First, the modeling scenarios are defined to specify the scope of the data analysis and this research.

3.3.1. Modelling scenarios

The modeling scenarios are determined to find the situations that are simulated in the transport model. There are 3 main scenarios for which the transport model is designed, and the scenarios are as follows:

- Baseline scenario with normal water levels
- Drought scenario with low water levels
- Drought scenario with the implementation of transport hubs

The Baseline scenario will show the normal transport flows during average periods where the vessel capacity is average. The drought scenario will simulate periods of drought similar to recent periods of low water discharges and will depict the difference between IWT flows during periods of low water levels. In the third scenario, the transport hubs at Nijmegen, Duisburg, and Kaub will be implemented into the drought scenario and show the influence of the hub on the improvement of the network capacity.

3.3.2. Data collection and analysis

When the design scenarios are determined, data can be collected and looked at that corresponds with these scenarios. For this, data can be used from Rijkswaterstaat and the Port of Rotterdam, which show the cargo transported over the Rhine against different water discharges. Water discharges, water levels, and historic transport data can show the reduction of transported cargo via the inland waterways during periods of drought compared to the baseline (average) scenario. These reductions will be determined for the areas lying around each bottleneck to determine the necessity of the transport hub. The corresponding vessel fleet of the scenarios will be examined to find the design vessel for the modeling cycle. Based on historical data on water levels, the average available loading depth of the vessel will be determined for the same areas for which the cargo transport reduction is determined.

3.4. Transport hub location analysis

As described in section 3.1, the three identified bottlenecks are located in Nijmegen, Duisburg, and Kaub. Around these locations, it is essential to find suitable spots for the transport hubs. Existing terminals with port infrastructure are considered, along with other potential areas that could serve as interesting locations for the hubs with different characteristics.

The characteristics need to be graded using a scientific method to find the most efficient locations for future transport hubs. Different scientific grading methods are investigated to find a suitable method for this research. Two types of grading methods are looked into, mathematical optimization and MCDM methods (Multi-Criteria Decision Making). Mathematical optimization will require data on all the variables of the potential locations to perform calculations. This data is hard to retrieve and may not even be available for all potential locations. Gathering and researching all this data on the potential locations would cost too much time for the scope of this research. Therefore, in this research, only the MCDM methods are considered. Different methods are considered and compared to find the most suitable method for this research.

3.4.1. Multi-Criteria Decision Making Method

From Liang et al., 2021, the Best-Worst method (BWM) can be used as many experts are available via the Port of Rotterdam to give an opinion on the characteristics and the weight of each characteristic. The AHP model (Analytic Hierarchy Process) from Professor Saaty, 1990, can be used which also weighs the criteria and calculates the favored alternative, in this case, the location for the transport hub. This method is, however, more complex than the BWM due to the increase in pairwise comparisons. The DEMATEL method (Decision-Making Trial and Evaluation Laboratory) can be applied to resolve intricate problems connected with multiple interrelated criteria using a structural modeling approach (Ogrodnik, 2018). Lastly, the TOPSIS method (Technique for order of preference by similarity to ideal solution) will be looked into as it also compares alternatives based on a set of pre-specified criteria (Chakraborty, 2022). All methods with their attributes are put in Table 3.3, which is based on the research of Vassoney et al., 2021, where MCDM methods are compared. In this research, the VIKOR method and WPM method (Weighted Product Method) scored best, so these are also taken into account as potential grading methods. The research didn't consider the BWM and the DEMATEL methods, so other literature is investigated to find comparisons between these methods and the other methods. From Liang et al., 2021, it states that the BWM is more consistent, easier to use, and widely used, so highly, and therefore receives High quality on each attribute. DEMATEL is used often but, in many cases, in combination with other MCDM methods like VIKOR, GRA, and ANP (Tzeng and Huang, 2012). Therefore, this method would be even more complex and harder to implement than the VIKOR method on its own. That's why the DEMATEL method scores Medium on ease and feasibility.

The results from Table 3.3 and the fact that the terminal case from F. Liang et al. is similar to this research, the MCDM method used to find suitable transport hub locations is the BWM. Experts at the Port of Rotterdam and the TU Delft can give their input via this method to determine the weights of each characteristic in the location analysis.

3.5. Ethical reflection on research methodology

An ethical reflection for the research methodology is made based on potential risks. For this research, the risks primarily stem from the handling and utilizing data and models provided by various parties and institutions. Therefore, a data management plan is written with an extensive overview of the safety risks.

Method	Description	Feasibility	Ease and Transparency	Consistency
BWM	Method to evaluate a set of alternatives with respect to a set of decision criteria based on pairwise comparisons of the decision criteria.	High	High	High
AHP	Analytic hierarchy process, which relies on pairwise comparisons of the alternatives on each criterion and an additive aggregation to calculate the overall performances	Medium	Medium	Medium
DEMATEL	Multicriteria decision-making method based on asymmetric linguistic comparison matrices that enable the capture of causal relationships between criteria.	Medium	Medium	High
TOPSIS	The Technique for Order Preference by Similarity to Ideal Solution, in which the alternatives are ranked based on their distance from defined ideal and negative-ideal solutions	Medium	Medium	Low
VIKOR	Multi-criteria optimization and compromise ranking, which seeks the compromise solution based on the closeness to a defined ideal solution	High	Medium	High
WPM	Weighted product method, in which the alternatives are compared by multiplying different ratios, one for each criterion, raised to the power of the corresponding weight	High	Medium	High

Table 3.3: Comparison of Various Decision-Making Methods

Another important factor is not going outside the scope of the research and staying focused on the research questions. For instance, a design cycle was considered to be included at the end of the research, but that turned out to be too difficult to complete within the allotted time. When the results are finalized, it will be discussed how the hubs can be implemented and for which cargo throughputs the hubs are interesting, but the cycle is left out of the methodology.

A key factor of this research being part of the European project CLARION is that the openly available and open-source model can be reused for future purposes in the field of Ports and Waterways. Therefore, the model is uploaded and openly available via GitHub, and explanations are given in this thesis.

4

Transport competition model

This chapter will give a description of the developed Python-based transport model for competing modes of transportation and sea ports. This model will help simulate the port-hinterland competition network and show the cost effectiveness of integrating transport hubs. An overview is given about the requirements, use, and inputs of the model. Explanations are given about transport cost calculations and the used transport networks to determine the trips for each modality. Methods are created to integrate different water levels, transport hubs, and emissions into the model. Using these integrations and the found critical bottlenecks from section 3.1, an answer will be given to the second research question:

How can we model port-hinterland transport competition for different seaports and modalities, and how can transport hubs be implemented into this model?

This model will then be integrated with inputs from the data analysis and the exact locations for the hubs from the transport hub location analysis. After this, the results of the different simulations from the transport model are shown in chapter 7.

4.1. Explanation of the python based transport model

In this subsection, we will provide a concise overview of how the model operates and explain how transport costs are calculated for each scenario. The model builds upon the principles of container transport, which also served as the foundation for the earlier Network-Competitiveness model from de Iongh, 2020. The current approach retains this basis while incorporating additional features to enhance accuracy, integrate the drought scenarios, and use inland transport hubs at Nijmegen, Duisburg, and Kaub. A full overview of the Python model and code is provided in Appendix B for a detailed explanation. The model is designed to meet the following objectives and requirements:

- The model must be reusable, open-source, and easy to operate with clear, well-defined steps. This ensures broad accessibility and encourages widespread adoption.
- The data utilized in the model must also be open-source, allowing universal access and enabling others to replicate or extend the analysis.
- The transport model should accurately determine the shortest routes for freight transport across water, rail, and road networks, ensuring reliable results.
- Reliable and comprehensive cost functions must be included in the model, facilitating the identification of the most cost-effective freight transport options.
- All described scenarios must be implemented within the model and should be directly comparable, allowing for a thorough analysis of different strategic alternatives.
- The model must provide visual outputs for all scenarios, highlighting the differences and making the impact of transport hubs visually clear and easy to interpret.
- The input parameters for the scenarios should be easily adjustable, enabling the model to be adapted for analyzing alternative scenarios and future use cases.

The model starts by identifying the origins and the destinations for which the port hinterland network can model the different types of transport. The Port of Rotterdam, the Port of Hamburg, and the Port of Antwerp were already integrated into the model to test the competitive connections to hinterland destinations. Other seaports can also be added to test their competitive nature towards hinterland destinations.

4.1.1. NUTS regions as hinterland destinations

The destinations for port-hinterland cargo transport are NUTS regions of European countries. The model was developed by using the centroids of these NUTS regions as the destination points, where the size of each NUTS region depends on the population living in that area. NUTS regions are used by the European Commission for "collecting, developing and harmonizing European regional statistics" and "carrying out socio-economic analyses of the regions" (Eurostat, 2024). NUTS regions are categorized on different levels, level 0 are the countries, and level 3 are small regions. The 2016 NUTS data is used in the model, being the most updated version of the NUTS regions, and is retrieved from Eurostat, 2024. The benefit of using level 3 NUTS regions is that the results are more specific per area, but it takes larger computing power to reach the result. While working on the model, the NUTS 2 levels will be used, with the final results presented at the NUTS 3 level for more specific outcomes.

level	classification	population size	number of regions
NUTS-0	countries		27
NUTS-1	major socio-economic regions	3.000.000 - 7.000.000	92
NUTS-2	basic regions (for regional policies)	800.000 - 3.000.000	244
NUTS-3	small regions (for specific diagnoses)	150.000 - 800.000	1165

Table 4.1: Different levels of NUTS-regions (Eurostat, 2024)

For the desired simulation, an area of Europe can be chosen in the model for which the hinterland destinations are filtered. Using this method and changing the area gives the possibility to simulate the whole of Europe or just a small section consisting of the Netherlands, parts of Germany, and Belgium. The difference between a small area and a large area is shown in Figure 4.1 and Figure 4.2 and are both level 3. The small area is convenient while updating and working on the model with shorter computing times, and a larger area would be interesting if other seaports were also integrated into the model. In the model, it is possible to draw a polygon of the outline of the interested European area, which can be used for the simulations.

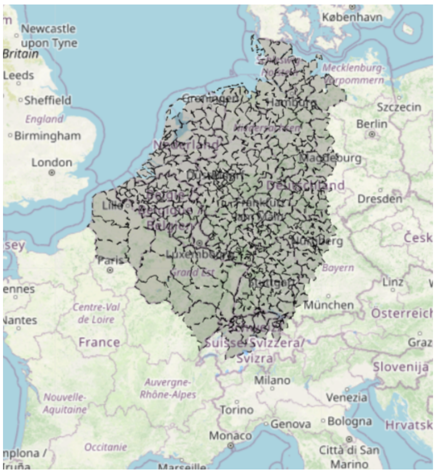


Figure 4.1: Small European area for simulations

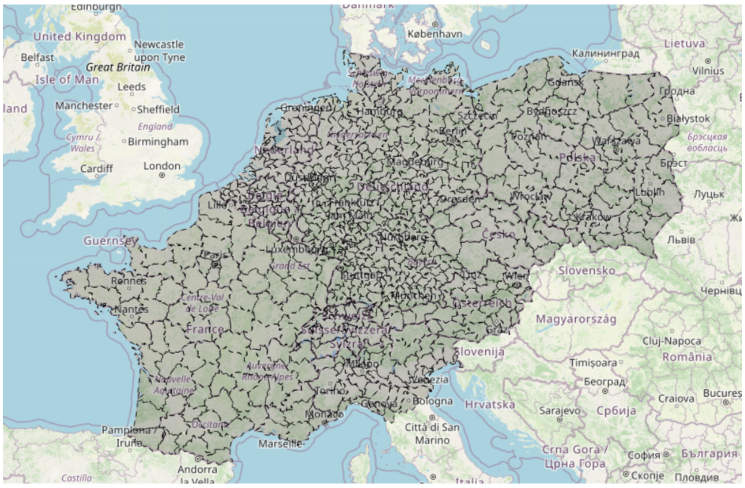


Figure 4.2: Big European area for simulations

4.1.2. Model use

To work with the model and run simulations through the model, a schematic overview is created in Figure 4.3. The model is created for container transport, and therefore, the cargo that is simulated to be

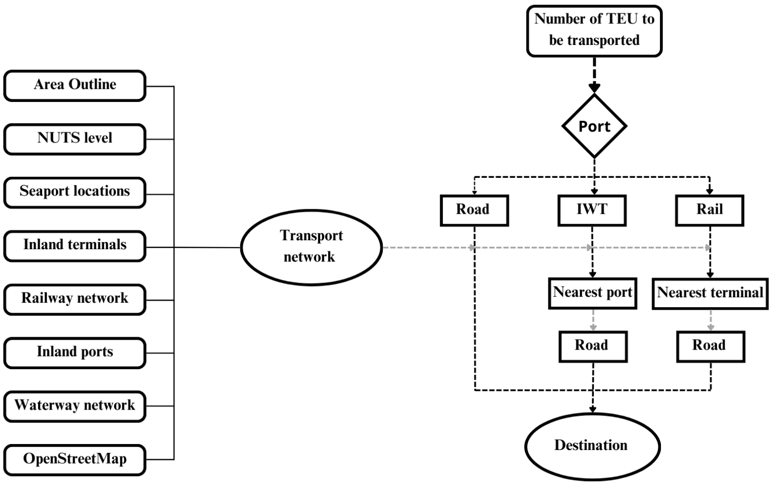


Figure 4.3: Schematic overview of the transport model and the transport Network

transported is expressed in TEU. The exact location of the seaports can be determined when it comes to the location inside the port area. The NUTS level is also an input for the model to define the precision and the computing power necessary for the simulation. The outline of the interested area can be picked as explained in subsection 4.1.1, and the type of networks are described in section 4.3.

On the left side of Figure 4.3, the inputs for the transport network are shown, and on the right, the big steps in the model. For each seaport, the shortest route towards the destination is determined for the different modalities. IWT and rail transport can't reach most of the destinations via the transport network, and that's why last-mile truck transport is taken into account. The closest port or terminal to the destination is found, and from these locations, the last-mile transport is determined. Using the determined route to the hinterland destination, the cost of the transport can be calculated, and the cheapest modality and seaport can be found. A full explanation of how to work with the model is written in Appendix B where a step-by-step guide is given on how to work with the model.

4.1.3. Integration of water levels into transport model

To accurately determine the influence of water levels on IWT, a way is designed to add water level limitations to hinterland destinations. The old model assumed that every waterway was the same, where vessels could sail at maximum capacity, but water depth is the most important factor of inland waterway transport, especially in areas that are prone to low water levels. This research uses 4 areas for the data analysis, and the same areas will be used for the water depths in the transport model.

The 4 corresponding areas will have loading capacities and loading depths depending on the data of the baseline scenario or the drought scenario. These capacities are precisely determined in chapter 5 and will be implemented using polygons for different areas in Europe corresponding to the water depth of the 4 areas. The hinterland ports lying in the same area, similar to the water depth before Nijmegen, are assigned water depth value 1, and hinterland areas lying beyond Kaub are assigned water depth value 4. Other waterways are also included with the same value because these are also prone to low water levels. The simplified assumption is made, however, that the terminals reached by other waterways will have similar loading capacities to the Rhine. Creating accurate loading capacities for each waterway would take extensive work and computing power, and because the transport hubs are only implemented along the Rhine, the other waterways are simplified.

In Figure 4.4, the water depth polygons are cut off for the matching outline of the NUTS regions that are considered for modeling. The same water depth polygons could be used for larger simulations but are less accurate for the other waterways. If other areas and waterways are considered, new loading capacities and new areas must be created to match the area.

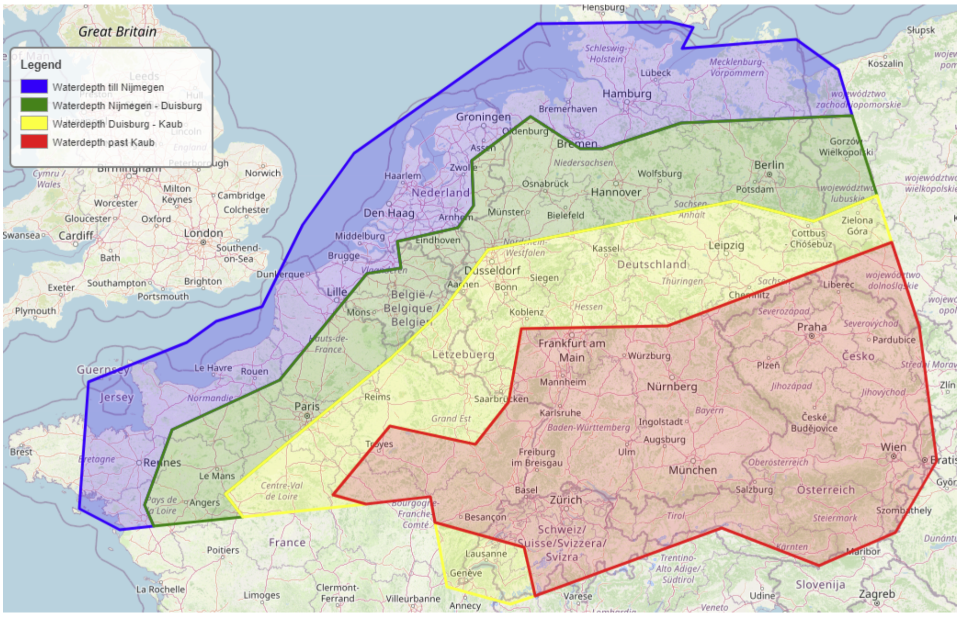


Figure 4.4: Polygons to represent the water depths of the 4 different areas

4.1.4. Model Assumptions

Creating a model to simulate every aspect of the European transport network and fully represent port-hinterland competition would be highly intricate and beyond the scope of this research. For this reason, assumptions have been made to simplify the modeling of cargo transport to, from, and through the Port of Rotterdam, as well as the other competing seaports. These assumptions help streamline the analysis while still capturing the essential dynamics of the transport system. When working with the transport model, a few key assumptions need to be kept in mind:

- The focus of the model is on the port of Rotterdam and the competitive regions where the port of Rotterdam is active. While the model can be extended to other regions, the model is used for the North-Western part of Europe. The Port of Antwerp and the Port of Hamburg are included in the model because they are the two largest ports in the region, alongside the Port of Rotterdam. Other ports, such as Le Havre, Amsterdam, and Bremen, could be considered later, but to avoid overcomplicating the base of the model, these will be added at a later stage.
- The model's foundation is based on a design ship that transports a load of containers to the hinterland. The same ship, equivalent to a large Rhine vessel, is used repeatedly until all the cargo has been transported. There are no limitations regarding the availability of the design vessel, meaning there is no shortage considered in the model. Other vessel sizes could be considered later, but to avoid overcomplicating the base of the model, one design vessel is used.
- As well as the design vessel, there's also a design truck and a design train which limits the possibilities of other modalities.
- Only the cargo transport from the seaports to the hinterland destinations is considered, based on the simplified assumption that the return trip to the seaports will be the same as the outbound journey. Additionally, only the costs for the outward journey are considered assuming that vessels carry different cargo on the way back.
- To avoid many different water levels in the waterway network and to simplify the number of different water depths along the different routes. Only 4 different water depths are entered into the model, along with the corresponding vessel capacities. Every river stretch has a different water level for each scenario, and dynamic water levels could be added in future research.
- Delays are not taken into account in the model. Transport is well coordinated, and ships, trucks, and trains are ready when needed without network restrictions. This also means that no costs for delays are included.

- The capacity efficiency is assumed to be as high as possible. This means that a vessel, truck, or train is always loaded to its maximum capacity, which is in real life not realistic.
- The port and terminal handling costs and waiting times are also generalized, and it is assumed that each location will have the same expenses for handling cargo. In reality, each port has its advantages and problems, which affect costs on an individual level.

4.2. Transport modality cost calculations

Extensive research has been done by Panteia to determine cost figures for freight transport (Meulen et al., 2023). The base year 2018 was taken in the report to get information from datasets. Cost figures were determined per vessel type and cargo type for the year 2021, which was an average year when compared to the past 10 years. The average net weight of a container is 15.5 tonnes, and this is used when calculating in per tonne units needs to be translated to per TEU units (Limbourg and Jourquin, 2009). This already takes into account the empty containers and can be used for implementing cost numbers by €/ton/km and transforming these to €/TEU/km.

4.2.1. Road transport cost calculation

The equation for calculating a certain amount of cargo transport from a seaport to a certain destination in the hinterland is determined by adding the cost per kilometer for each LZV truck that carries 2 containers with the waiting time at the terminals. In the research from Panteia, the same method is used to calculate the cost of a trip from origin to destination.

$$\text{cost}_{\text{truck}} = (€43,45 \times \text{t}_{\text{terminal}} \times 2 + \text{d}_{\text{trip}} \times €1,86) \times \text{trips} \tag{4.1}$$

€1.86 is the cost per km of a LZV truck, and €43.45 is the waiting cost per hour during handling. 20 minutes is chosen as the truck waiting and handling time derived from the APM Terminals, 2024. The kilometers traveled are first chosen to be 1 way, assuming that other types of cargo are transported from the destination back to the origin.

4.2.2. Inland waterway transport cost calculation

For the cost calculation of the cargo transport over the inland waterways, the same report from Panteia is used. Here, the cost per kilometer and waiting cost for the vessel are added to the cost of terminal time. Because different Nuts regions are used in the model, which can't all be reached by boat, the nearest port is found, and from there, the last-mile truck cost is added to the inland waterway transportation cost. The kilometer cost for the chosen vessel is €18.47, with a terminal cost of €105.23 per hour. The terminal time is calculated by adding up the entering time into the port, the handling time, and the leaving time. 10 minutes is chosen for entering, 10 minutes for leaving, and a loading speed of 30 TEU per hour corresponding to the capacity of 1 operating crane.

The terminal costs are not openly available due to competitiveness and the fact that most cargo is handled in larger batches combined with transport instead of per cargo unit for transshipment. As discussed with experts from the port of Rotterdam, specialized in inland container transport, a terminal handling fee of €40 per TEU can be assumed and is added to the cost function. This value is checked by comparing the terminal cost calculated by Lun and Cariou, 2009. Here, the most efficient terminals achieve a cost per TEU just larger than €30, and assuming that the inland terminals are less efficient, the value of €40 is taken per TEU for terminal costs.

$$\text{cost}_{\text{vessel}} = (€105,23 \times \text{t}_{\text{terminal}} \times 2 + \text{d}_{\text{trip}} \times €18,47) \times \text{trips} + \text{cost}_{\text{truck}} + 2 * €40 * \text{nr}_{\text{TEU}} \tag{4.2}$$

Here also only the trip from the origin to the destination is taken into consideration and not the trip back to the seaport. As described in subsection 5.2.2, the average vessel turned out to be an M8 vessel for container transport. This vessel can carry up to 208 TEU and will be used as the design vessel in the model (Otten et al., 2017). With this, the necessary number of trips is determined to transport cargo from the seaports to the nuts regions in the hinterland. Other vessels can also be used in the model by changing the capacities for each hinterland region based on the scenarios determined in Table 5.1 and the loading rate of the vessel based on Table 5.2.

4.2.3. Rail transport cost calculation

The rail transport calculation is done similarly to the IWT cost calculation using the Panteia report. Here the waiting cost per hour is higher at €462.17 per hour and €17.55 per km travelling by train. The capacity from the train is derived by using the long train for container transport, which can have a capacity of 90 TEU (Otten et al., 2017).

$$\text{cost}_{\text{train}} = (€462,17 \times t_{\text{terminal}} \times 2 + d_{\text{trip}} \times €17,55) \times \text{trips} + \text{cost}_{\text{truck}} + 2 * €40 * \text{nr}_{\text{TEU}} \qquad (4.3)$$

The last-mile transport to reach the destination is also done here by truck, as is done with the IWT. The terminal costs are added here at the same prices as the vessels. The only aspect different from the vessels is the arriving and leaving time, which is 5 minutes each. For 1 fully loaded train, this would be 5 + 90 * 2 + 5 = 190 minutes of waiting and terminal time.

4.3. Transport networks used in transport model

As mentioned in the modeling scenarios, three ways of transport are compared and need to be integrated into the model. The IWT, rail, and road networks through Europe are integrated into the transport model to find the ideal transport mode for each hinterland destination. Different data types for these networks are available and are considered to integrate in the model. The main goal is to use the same networks already used by other parties in the CLARION project to maintain transparency and make it easier for the other parties to use this model.

4.3.1. Road network

The base network-competitiveness model is updated for the road network to use OpenStreetMap, 2024, for the road network simulations. Using OpenStreetMap doesn't make use of a limited API key and can be, therefore, used more frequently and for more different simulations. The base model was limited to a certain amount of requests per day using the API function from Google Maps, and therefore, the change to OpenStreetMap needs to be made. From the different seaports and transport hubs, OpenStreetMap is used to find the shortest route and the travel duration. Combined travel options with different modalities will also be used in the same way, where the last-mile transport is determined via road from the closest port or railway terminal.

4.3.2. Rail network

The rail network used for the model shouldn't focus on all railway lines present in Europe but solely on the railway lines for freight transport. These are the railway lines where cargo can be transported and not passenger transport. The same transport network for railway lines already present in the model is also used by the parties in project CLARION. The ETISPlus data is used for the European railway network and is retrieved from Demis, 2022.

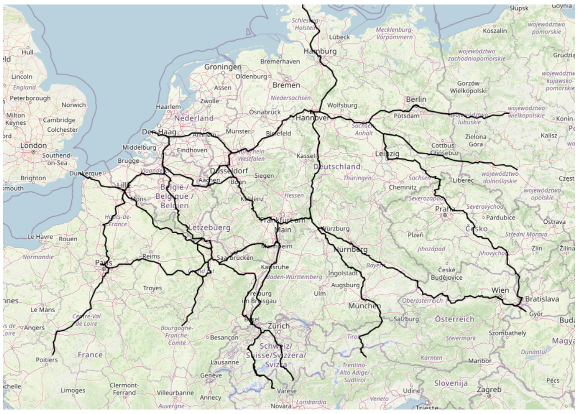


Figure 4.5: Railway transport network

Figure 4.6: Inland waterway transport network

4.3.3. Inland waterway transport network

For the inland waterway transport network, the ETISPlus waterway networks are used along with the inland ports and terminals. This IWT network is also used by other partners in the CLARION project, and an older version of the network is also used in the Network Competitiveness model. The waterway networks are retrieved via Demis, 2022 ass well and provide the main waterway networks through Europe. EuRIS, 2023 is also looked at due to the more extensive information on each waterway stretch provided in the data; however, working with this network in the model turned out to be harder than expected. To determine the route for each trip, the shortest path method needs to be solved, but with this network, the shortest path couldn't be found due to gaps between edges and nodes. Therefore, the ETISPlus waterway network is preferred and used in the transport network model. An IWT network where water depths of the waterway are integrated would be a great extension for further development of the model

4.3.4. Inland ports and terminals

The data for the inland ports and terminals have been checked to see if they are still up to date. The data for inland ports in the model has been taken from UNECE, 2017, and the data for rail terminals has been obtained in the same way as the railways via Demis, 2022. For both databases, there was no further updated version, and the data were still accurate when compared to the data from European Commission, 2024. The closest hinterland port or terminal to the centroid of a NUTS region will be the destination for the trip over water or rail. From these points, a last-mile truck transport is carried out to reach the destination. In Figure 4.7, the inland ports are shown as light red dots and the terminals as dark red dots. The IWT network is shown in blue, and the railway network is shown in black.

4.4. Integrating the transport hubs into the transport model

To determine the impact of the transport hubs on the drought scenario, the transport hubs are integrated into the transport network. The transport hubs will only be used from the port of Rotterdam to check whether it improves the competitive position of the port compared to other seaports. Using the transport hubs in the model won't make it that more complex. The complete transport network that's used in the model is shown in displayed in Figure 4.7 along with the transport hubs at Nijmegen, Duisburg, and Kaub.

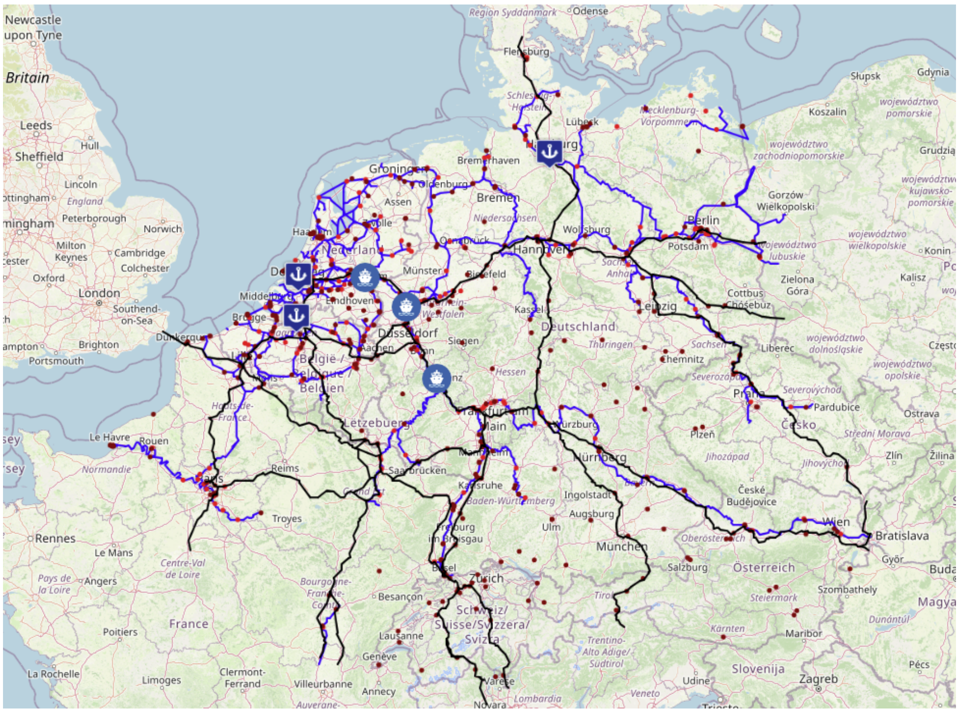


Figure 4.7: Complete transport networks used for running simulations in the model, dark red dots representing train terminals and light red representing inland ports

4.4.1. Transport hub implication into transport model

For each transport, the first part of the trip is by water to the transport hub. From the hubs, road, rail, and waterway transportation are calculated to determine the costs for transshipment to each of these modalities. For road transport, this will be the same use as normal water transport, but the end destination is at the transport hub with a longer last-mile truck transport.

For IWT, the cargo is loaded off the first vessel coming to the transport hub and reloaded onto a new vessel leaving the transport hub. For the first vessel, the location of the transport hub determines the vessel capacity, and for the second part of the journey, the destination determines the vessel capacity. After both journeys, a last-mile truck transport is still necessary.

For rail transport, the cargo is transshipped from the vessel to the rail modality, where the origin is the transport hub, and the destination is the hinterland NUTS region. Last-mile transport is also still necessary here, and because Nijmegen has no rail access, the possibility of transshipping to trains here will be removed from the potential outcomes.

4.4.2. Added costs transport hub

The costs for road transshipment will be calculated the same way as normal waterway transport but with a longer last-mile truck distance. For IWT and rail transport, extra terminal costs are added to the transport price due to extra handling of the cargo. Here, the assumption is made that the terminal costs include transferring from water to rail.

Different options for the transshipment costs are modeled and depend on the assumed activities for transshipping to rail and back to water:

- 2 times extra terminal costs added for unloading and loading for all containers. Extra costs will be twice the waiting and terminal costs of €40 per TEU, this will be around €90 extra per TEU.
- 1 time extra terminal costs for immediately placing cargo on other modality for all containers. Additional costs will be 1 terminal handling and waiting time. This will be around €50 extra per TEU.
- 0,5 times extra terminal costs added for all containers, resulting in €30 per TEU extra. Here, it is assumed that not all cargo needs to be transshipped, and the total terminal costs are lower per TEU. The more exact possibility of only transshipping cargo that exceeds the loading capacity past the hub will be discussed as well. But this variant is simpler to implement and to see the benefits of low transshipment costs.

4.5. Seaports

For the model's base, Antwerp and Hamburg have already been added to simulate the competition from other seaports towards the hinterland regions of the Port of Rotterdam. Other European seaports like Bremen, Amsterdam, Groningen, Marseille, Genoa, and Le Havre could also be considered to test a more extensive hinterland competition in the North-Western European hinterland. Other could also be integrated to check competitive areas in other European regions. Research is already been done by Panteia and the Port of Rotterdam where the hinterland costs and market position of the port of Rotterdam are checked with hinterland seaports. The outcome of this cheapest seaport for hinterland competition is shown in Figure 4.8 and can be used to configure the model for the baseline scenario to check the resemblance to this previous research.

4.6. Emissions

Emissions are added to the model to give the environmental impact of the transport hubs on the transport network. The emissions for vessel, truck, or train type are taken from Otten et al., 2017, where the energy use is given in g/tonkm. The emission factors are put in Table 4.2. The average train is taken for a ratio of 80% - 20% for all emissions. There is one problem with using the average values into the model, there would be no difference in sailing more often with less cargo when it comes to emissions. The report also shows MJ/km for each modality of light capacity and heavy capacity. This factor is used for each type of transport to differentiate the emissions at lower vessel loading rates. The results are shown in Table 4.3, where the full capacity factors for train and truck are used at respectively 132

Figure 4.8: Cheapest seaport: which port has the lowest hinterland transport costs (Gille and van Schuylenberg, 2022, & de Leeuw van Weenen et al., 2019)

Vehicle/Vessel	Type of freight	C02 (g/tkm)	PMc (g/tkm)	NOx (g/tkm)
Tractor-semitrailer, heavy (2 TEU)	Med.-weight	102	0,004	0,36
Train, long (90 TEU)	Med.-weight	18	0,002	0,06
Large Rhine vessel (208 TEU)	Med.-weight	24	0,009	0,26

Table 4.2: Emission values for different transport modes (Otten et al., 2017, table 4)

MJ/km and 13,2 MJ/km. The emission factor based on the loading rate for the design vessel is shown in Equation 4.6 and is created in the same manner as Equation 5.1. Here the e_{full} = 362 MJ and e_{empty} = 102 MJ for the large Rhine vessel, using a simple linearization of the Table 4.3 energy use.

Vehicle/Vessel	light	med.weight	heavy	
Train, long (90 TEU)	76,2 MJ/km 40%	92,4 MJ/km 80%	130 MJ/km 98%	loading rate
Large Rhine vessel (208 TEU)	206 MJ/km 40%	257 MJ/km 65%	310 MJ/km 80%	loading rate
Tractor-semitrailer, heavy (2 TEU)	8.5 MJ/km 0%	10,85 MJ/km 50%	13,2 MJ/km 100%	loading rate

Table 4.3: Vehicle and Vessel energy use based on loading rate

$$e_{\text{vessel}} = e_{\text{empty}} + ((\text{water level} - \text{ukc}) - LD_{\text{empty}})/(LD_{\text{full}} - LD_{\text{empty}}) * (e_{\text{full}} - e_{\text{empty}}) \tag{4.4}$$

Emission factor	g/MJ	Source
CO_2	71,05	23,42 g diesel/MJ × 3034 g CO_2/kg diesel
N_2O	$5,85 \times 10^{-4}$	23,42 g diesel/MJ × 0,025 g N_2O/kg diesel
CH_4	$4,92 \times 10^{-3}$	23,42 g diesel/MJ × 0,21 g CH_4/kg diesel
SO_2	$4,68 \times 10^{-4}$	23,42 g diesel/MJ × 0,02 g SO_2/kg diesel

Table 4.4: Energy converted to emission factors (Otten et al., 2017, Table 51)

A figure of 42,7 MJ/kg for the energy density of diesel (100% fossil) is used, and for each kilogram of diesel, the emission factors are put in Table 4.4. The energy use will be added to the model in the same way the water depths are integrated into the model and will show the sustainable advantage of the hubs. First, the transport data needs to be analyzed to find characteristics of the modeling scenarios, vessel capacities, design vessels, and cargo throughput at the transport hubs.

5

Data analysis and model input

The data analysis is carried out to find input data for the transport competition model and find characteristics of the different modeling scenarios like water levels and vessel capacities. Cargo throughput is looked at for both scenarios to determine the necessary capacities at the transport hubs. Here different datasets of water levels and cargo throughput are analyzed to find the design loading depths, vessel fleet, and cargo transport to answer the third research question:

How much cargo must be relocated on another modality at the hub locations to guarantee the reliability of the hinterland shipping network for a critical low water level?

As explained in section 2.5, the CLARION objective is to assure 80% operability during disruptions of extreme weather events. Analyzing the cargo throughput will give an inside into the reduction, where it can be determined how much cargo benefits from a cargo transshipment via a transport hub.

5.1. Modeling scenarios

The modeling scenarios are determined to find the different situations that are simulated in the transport model. There are 3 main scenarios, corresponding to two water depth scenarios, for which the transport model is designed, and the scenarios are as follows:

- Baseline scenario with normal water levels
- Drought scenario with low water levels
- Drought scenario with the implementation of transport hubs

The Baseline scenario will show the normal transport flows during average periods where the vessel capacity is on average. The drought scenario will simulate periods similar to 2018 and 2022 and will depict the difference between IWT flows and rail and road transport. In the third scenario, the transport hubs at Nijmegen, Duisburg, and Kaub will be implemented into the drought scenario, and the influence of the hub on the favored modality will be shown.

First, the baseline scenario is considered, and the average water discharge and the associated water levels for this discharge are determined. The discharge data from Rijkswaterstaat show that the average discharge at Lobith over the past 25 years is 2090m^3/s(Rijkswaterstaat, 2024b). For the drought scenario, the 180 average of the drought periods of 2018 is taken based on the research from the University of Twente. This mean water discharge is 1017m^3/s (van Brenk, 2021). For 5 months, low water levels were measured in 2018 from half of July till mid-December in Kaub and from half June to half October in 2022 (Power BI PoR, 2024). For Lobith and Ruhrort, this was around the same period except for 2022, when the water level problems started in July till September. Therefore, the period of drought that is used for an input of the drought scenario is mid-July (16th) to mid-December (15th) 2018 and July to September 2022. For these periods the average water discharges at Lobith are found using the data from RWS and turned out to be 960m^3/s, which will be used for further calculations and modeling. For the 153 days in 2018, there were 114 days at Kaub where the water level was below 80 cm, which is the minimum depth established for sailing at which shipping contracts cease to apply. In 2022, this was 46 out of 92 days, with 37 consecutive days below the low water threshold, which was 82 consecutive days in 2018. The water depths are determined with the help of the digital twin of the Port of Rotterdam and the RWS water information for locations Wesel, Ruhrort, Oberwinter, Bonn, and Bingen. The discharges used in the model and the corresponding water levels before the bottlenecks for both scenarios are entered in Table 5.1, which are the average loading depths for the drought period in 2022. For Nijmegen, the minimum water depth of 2.80 m is used, which results in a loading depth of 2.60 m with an under-keel clearance of 20 cm for a container vessel passing a hard bed layer (van Dorsser et al., 2020).

model input	baseline scenario	drought scenario
discharge at Lobith	2000m^3/s	1000m^3/s
Loading depth till Nijmegen	370 cm	260 cm
Loading depth till Duisburg	350 cm	236 cm
Loading depth till Kaub	288 cm	215 cm
Loading depth past Kaub	232 cm	169 cm

Table 5.1: loading depths and discharges for model

The average scenario will be based on the average of all available IVS data, which is from the past 4 years. The inputs for the drought scenario will be based on the average values during the 2022 drought period. The water levels mentioned in Table 5.1 are determined for this period as well, using data from Rijkswaterstaat measured at the gauges along the Rhine. The loading depths are determined by using the average gauge levels and implementing them in Equation 3.1. For Kaub, the water level measured at Gauge Kaub is 83 cm lower than the loading depth in Table 5.1, and looking at Figure 5.1 the loading capacity is a little over 25% during the drought scenario. Using Figure 5.1 and the water levels at Kaub it can be determined that the loading depths of a large Rhine vessel are as follows:

- **Loading depth full capacity large Rhine vessel: 333 cm**
- **Loading depth half capacity large Rhine vessel: 218 cm**
- **Loading depth empty large Rhine vessel: 103 cm**

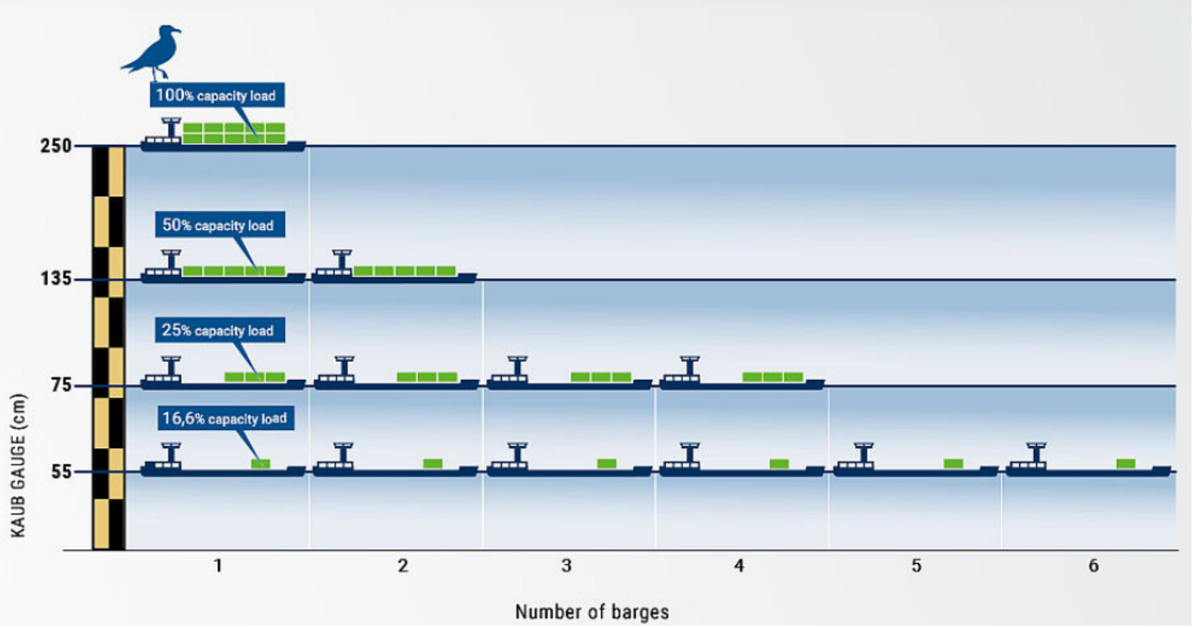


Figure 5.1: Capacity of container vessel at Kaub (Contargo, 2024)

These vessel loading depths are determined for all vessels by van Dorsser et al., 2020 and made the knowledge on vessel loading rates available on an aggregated level by looking at more than 100 different vessels. Functions and notebooks are open source and available via the GIT repository OpenTNSim, where the empty vessel draughts and full capacity vessel draughts can be found (van Koningsveld and Baart, 2020). The same loading depths for the large Rhine vessel are found along with other container vessels, tankers, and dry bulk vessels. The model for determining the Dead-weight tonnage, empty draught, and maximum design draught is shown in Equation 5.1, which results in the container vessel data shown in Table 5.2. The loading depth of low water and the low water tonnage are the minimum values for the vessel where it makes sense to sail. Lower than this level, sailing is still possible but it is assumed that the costs don't outweigh the benefits.

$$\mathrm{DWT} = -16,69 + 0,97 * \mathrm{L} * \mathrm{B} * \mathrm{T}_{\mathrm{design}} - 1,1 * \mathrm{L} * \mathrm{B} * \mathrm{T}_{\mathrm{empty}} \tag{5.1}$$

CEMT class	Length	Width	loading depth full	loading depth low water	loading depth empty	full tonnage	low water tonnage
III	63	7,00	2,78	1,2	0,87	754	130
IV	85	9,50	3,16	1,3	0,96	1610	250
V	110	11,45	3,50	1,4	1,00	2882	461
VI	135	14,25	3,93	1,5	1,01	5169	863
VI+	135	17,50	4,22	1,5	1,07	6868	945

Table 5.2: Container vessel capacities for empty, full, and minimum sailing conditions (van Dorsser et al., 2020)

Using the available loading depths at locations and the characteristics of the design vessel, the necessary trips can be determined to transport a certain amount of containers from the seaport to a hinterland terminal. A formula is created from Table 5.2 to determine the vessel capacity if full loading depth, empty loading depth, and water level are known:

$$\mathrm{capacity}_{\mathrm{vessel}} = ((\mathrm{water\ level} - \mathrm{ukc}) - \mathrm{LD}_{\mathrm{empty}})/(\mathrm{LD}_{\mathrm{full}} - \mathrm{LD}_{\mathrm{empty}}) * \mathrm{capacity}_{\mathrm{full}} \tag{5.2}$$

The under-keel clearance is taken between 20 and 30 centimeters, depending on the riverbed. Comparing IVS data during the drought scenario with the data from the baseline scenario will reveal the difference in vessel fleet composition and loading rate for both scenarios. The outcome of the different vessel fleets for each scenario can determine the design vessel for the transport model.

5.2. Transport Data analysis

The data analysis is carried out to find inputs for both scenarios in the transport model. Design vessel, loading rates, and cargo volumes are determined to know the efficient size of the transport hubs and the transport costs for a certain amount of cargo. For this, IVS Next data is used from Rijkswaterstaat and Port of Rotterdam, which show the transported cargo over the Rhine over the past 3 years (Rijkswaterstaat, 2024a). From this data, the origin, destination, cargo, and water discharge on the Rhine are important. An overview can be made of the transport flows from origin to destination through Europe, along with freight volumes passing through the identified bottlenecks. From this analysis an estimation can be made of the cargo that is delayed and the potential cargo that can be transferred to another modality at the transport hub. Figure 5.2 shows the transported cargo over the past years where 3 periods of reduced cargo transport are found, the holiday periods at the end of December and the dry period in the summer of 2022.

5.2.1. Transport reduction during dry periods

The IVS data is used to determine the average vessel capacity and vessel loading rate for both scenarios by looking at the average of all trips where cargo was transported. The outcomes are put in Table 5.3, where the CEMT class is added to give an estimation of the average vessel, A large Rhine vessel. Empty vessel trips are removed from the data, and the calculations are made for all trips to all destinations in the IVS dataset. The design vessel for both scenarios is fairly similar, and the loading rate is 14.7%

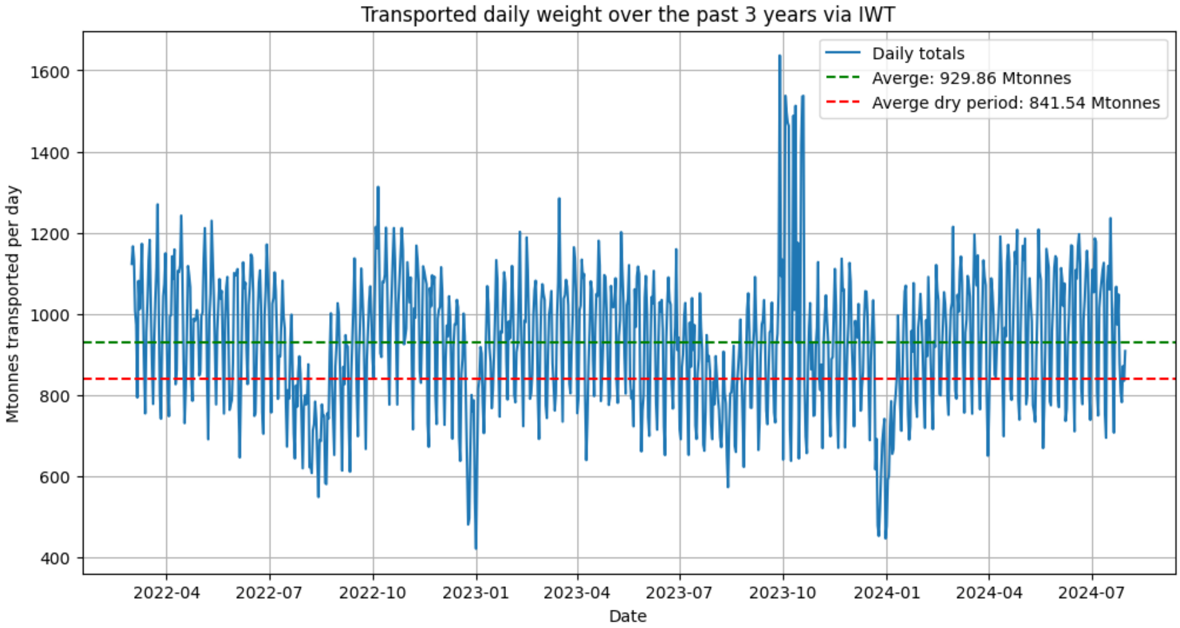


Figure 5.2: Daily cargo transported in Mega Tonnes (Rijkswaterstaat, 2024a)

lower in the drought scenario than in the baseline scenario. Now the destinations will also be taken into account. There are 1792 unique origins and 1867 unique destinations in the IVS data, and therefore, some filters need to be created. The first is the Port of Rotterdam as the origin of the trip and its unique destinations. Large hinterland destinations can be filtered and compared for different scenarios. From the port of Rotterdam, 802 unique destinations are found with 212 destinations lying in Germany. The top 10 destinations are looked at for both scenarios to determine the difference in loading rate. The outputs are put in Table 5.4 and show larger vessel sizes on average sailing to Germany with a far lower loading rate during the dry period. DELUH is located at Ludwigshafen which is past Kaub and has a loading rate almost twice as low in the 3 months of 2022 compared to the average loading rate. DESGW, Schwelgern, also shows a large decline due to the dry bulk terminal located here. Container terminals show less decline than dry bulk terminals because these vessels are not limited only by the drought but also by the space of the containers during the baseline scenario. This means that a fully loaded container vessel has a smaller loading depth than a dry bulk vessel. CEMT class defines the design vessel for the base scenario and the drought scenario based on the average vessel sizes. The largest Swiss locations are added to the table to showcase if the entire corridor is sailed from Rotterdam to Basel.

scenario	av. vessel capacity (tonnes)	CEMT Class	Transported cargo (tonnes)	Loading rate
Baseline	2646	Va - M8	1597	60%
Drought	2650	Va - M8	1362	51%

Table 5.3: Design values for different scenarios

The 20 largest hinterland destinations in Germany and the 2 largest hinterland destinations in Switzerland are shown in Figure 5.3 based on the number of vessel trips to these destinations. Visible is that 8 of the large destinations are passed Kaub and have to endure the low water levels in a drought period at this location. 5 locations have passed the threshold at Duisburg, and 9 locations have to pass the threshold at Nijmegen. These locations are used to determine the decline of transportable cargo passed each threshold.

origin	destination	CEMT base	CEMT drought	l.r. base	l.r. drought	Trips	cargo
NLRTM	DESGW	VIc	VIb	83,7 %	45,8 %	7359	dry bulk
NLRTM	DEDUI	VIa - M10	VIa - M10	45,9 %	35,3 %	5096	container
NLRTM	DEDHU	VIc	VIb	78,6 %	41,8 %	3214	dry bulk
NLRTM	DELUH	Va - M8	Va - M8	52,2 %	29,2 %	3037	container
NLRTM	DEEMM	Va - M9	Va - M8	34,9 %	28,5 %	1584	container
NLRTM	DENSS	Va - M8	Va - M8	58,9 %	41,9 %	1584	container
NLRTM	DEMHG	VIa - M10	VIa - M11	43,3 %	30,8 %	1508	bulk
NLRTM	DEDAT	VIa - M10	Va - M9	79,9 %	56,8 %	1363	bulk
NLRTM	DEMAI	VIa - M10	Va - M9	55,1 %	37,1 %	1352	bulk & cont
NLRTM	DEHMM	Va - M8	Va- M8	71,4 %	45,1 %	1175	bulk
NLRTM	CHFBL	Va - M8	Va - M8	62,6 %	36,2 %	773	bulk & cont
NLRTM	CHBSL	Va - M9	Va - M8	40,3 %	30,2 %	324	container

Table 5.4: Average vessel size and loading rate per largest German destinations and largest Switzerland destinations

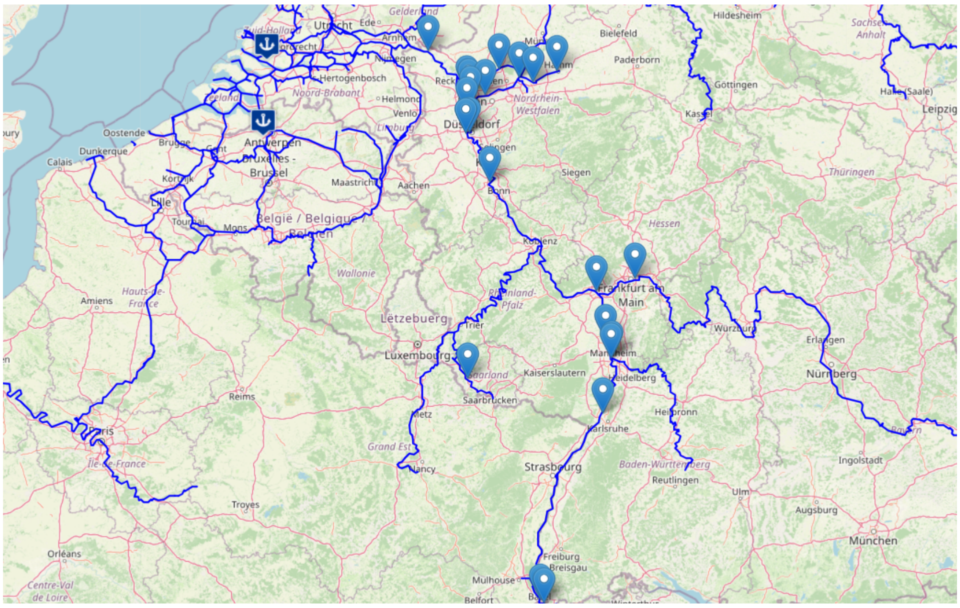


Figure 5.3: Largest German and Swiss hinterland destinations

Bottleneck	Nijmegen	Duisburg	Kaub
Destination	DESGW, DEDUI, DEEMM DEDAT, DEHMM, DEBOT DEMAL, DEWLM, DELUE	DEDHU, DENSS, DEGDO DEDIL, DEDUS	DELUH, DEMHG, DEMAI DEKAE, DEFRA, DEWOR CHBFL, CHBSL

Table 5.5: Largest vessel destinations past Bottleneck

Table 5.5 shows the largest destinations in Germany that lie past a certain navigable threshold and for which, by looking at the transport data, the cargo loading rate reduction can be determined for each threshold. For these destinations, the difference is made between dry bulk and container cargo to check the reduction for different types of cargo throughput for each transport hub. Here the cities from Table 5.5 represent sailing past each bottleneck. For container cargo, the IVS data was harder to filter because the number of TEU wasn't always noted while the transported weight was. Therefore making a clear distinction between container cargo and bulk is filtered if the numbers of TEU were greater than 0. This makes the number of container trips used for the data analysis smaller, but this was the only way to verify container transport against bulk. The results are put in Table 5.6 and Table 5.7.

Bulk Cargo	passed Nijmegen	passed Duisburg	passed Kaub
baseline loading rate	82,79%	76,73%	56,82%
drought loading rate	45,99%	41,25%	34,57%
transport weight baseline per trip	5316	5916	1399
transport weight drought per trip	2316	2418	886
average capacity baseline	6421	7710	2463
average capacity drought	5037	5861	2563
transported cargo per day baseline	94072	45349	13143
transported cargo per day drought	44340	19973	5731
increase of the necessary vessel fleet	230%	245%	158%
reduction of transported weight	-53%	-56%	-56%

Table 5.6: Change in transported cargo, in tonnes, for the baseline and drought scenario for Bulk

Bulk cargo shows a large increase in the necessary vessel fleet due to the reduced loading rate. Both cargo types show a large reduction in the amount of cargo transported to the German hinterland. The transported cargo reduction is significantly higher than the average cargo reduction shown in Figure 5.2. To keep the hinterland shipping network reliable, this would mean that a large number of the cargo must be relocated to another modality. Keeping in mind that the disruption-based availability of the network should remain at 80% based on the CLARION objectives. With an average transport reduction of 54%, this would mean that 46% percent of the cargo should be handled by the transport hubs to guarantee the reliability of the network and meet the CLARION objective during a critical drought. The transport hubs don't have to be the only solution to meet this objective, and previous research by Vinke et al., 2023 has pointed out that the used vessel fleet during periods of drought can work together with transport hubs to achieve the goal of making the network more resilient to climate change.

Container Cargo	passed Nijmegen	passed Duisburg	passed Kaub
baseline loading rate	27,75%	26,71%	20,63%
drought loading rate	23,73%	18,63%	17,96%
transport weight baseline per trip	1380	1255	1093
transport weight drought per trip	1165	909	1033
average capacity baseline	4973	4700	5296
average capacity drought	4908	4878	5750
transported cargo per day baseline	5058	1506	2320
transported cargo per day drought	3127	573	977
increase of the necessary vessel fleet	118%	138%	106%
reduction of transported weight	-38%	-62%	-58%

Table 5.7: Change in transported cargo, in tonnes, for the baseline and drought scenario for containers

5.2.2. Fleet composition

An analysis of the fleet composition is carried out to find the design vessel for both scenarios to enter into the transport model. The fleet compositions are analyzed for the drought scenario and checked if the vessels used during low water discharges decrease to handle cargo more efficiently. Vinke et al., 2023 proposed that coping with low water discharges by working efficiently with the available vessel fleet will decrease the costs for low-water sailing and will positively affect the waterway network's resilience. The same cities mentioned in Table 5.5 are used to check the fleet compositions for container and bulk vessels. The IVS data for vessel types is described in CEMT classes for container vessels and general cargo vessels and SK codes for bulk carriers. The vessel type is shown in the results in the SK code, but these are the same as the before-mentioned CEMT classes. Table 5.8 and Table 5.9 show the vessel fleets for the locations between bottleneck Nijmegen and bottleneck Duisburg, where the largest difference is the reduction of BII-6l vessels. The use of these vessels is reduced by 87.5 %, which results in a total reduction of 49.2% of the transported cargo from the Port of Rotterdam. The same is visible for the region beyond Duisburg and before Kaub in Table 5.10 and Table 5.11. The 54% reduction of transported cargo determined in subsection 5.2.1 is, therefore, mainly due to the decreased number of BII-6l vessels sailing towards the hinterland of the port of Rotterdam during drought periods.

SK code	Trips	% Weight handled	Weight/Day (tonnes)
BII-6l	4410	56,3%	72960,2
M8	3961	5,7%	7335,5
C3l	3210	12,1%	15634,4
M11	2007	3,1%	4074,5
M9	1536	3,8%	4903,8
M6	1314	1,2%	1604,0
BII-4	1224	9,8%	12720,9
M12	1067	1,9%	2468,3
C2l	703	2,0%	2566,8
C4	502	2,7%	3447,2

Table 5.8: passed Nijmegen vessel fleet baseline scenario

SK code	Trips	% Weight handled	Weight/Day (tonnes)
C3l	353	18,0%	10288,3
M8	318	6,9%	3926,3
M9	304	9,9%	5668,8
M11	244	7,6%	4377,2
BII-4	234	22,1%	12671,2
C4	157	11,7%	6690,8
M6	86	1,3%	759,8
BII-6l	80	16,0%	9151,3
C2l	79	3,2%	1812,5
M12	66	1,8%	1018,8

Table 5.9: passed Nijmegen vessel fleet drought scenario

SK code	Trips	% Weight handled	Weight/Day (tonnes)
M8	2632	10,6%	5528,0
BII-6l	1991	59,2%	30844,1
BII-4	915	17,5%	9098,7
M9	866	4,5%	2320,0
C3l	426	3,7%	1923,2
M6	340	0,8%	421,5
M12	169	1,1%	550,0
M11	155	0,8%	406,8
M4	120	0,1%	73,9
M7	64	0,3%	136,1

Table 5.10: passed Duisburg vessel fleet baseline scenario

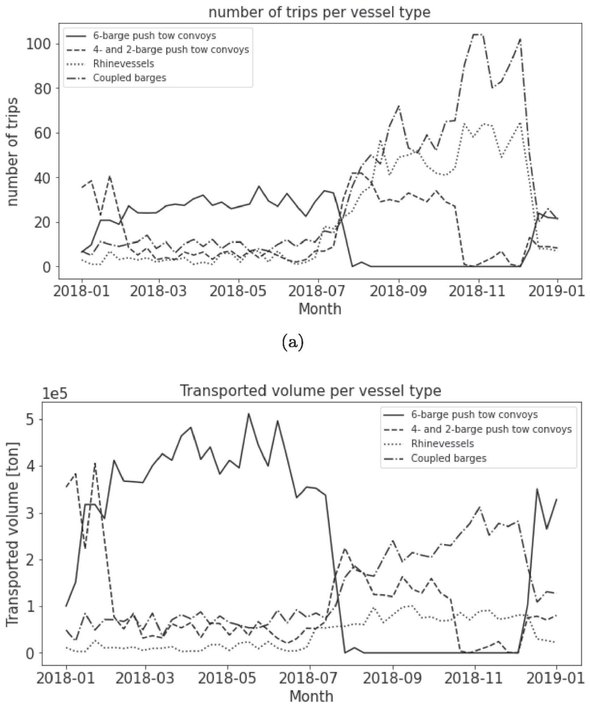
SK code	Trips	% Weight handled	Weight/Day (tonnes)
M8	253	13,3%	2683,5
BII-4	127	32,4%	6532,2
M9	118	9,8%	1967,0
C4	97	18,1%	3644,8
C3l	51	6,0%	1198,9
M6	41	1,7%	339,7
M12	31	3,6%	724,0
BII-6l	26	13,7%	2756,0
M5	7	0,3%	53,5
M7	6	0,4%	70,6

Table 5.11: passed Duisburg vessel fleet drought scenario

The BII-6l vessels are 6-barge push convoys, which are mainly used for transporting dry bulk (Otten et al., 2017). Regulations prescribe that for low water levels 6-barge convoys are not allowed to sail along the Rhine River (Vinke et al., 2022). Vinke et al. also show a shift in the deployment of vessel classes for the 2018 drought period in Figure 5.4, where the smaller 4- and 2-barge convoys are used more frequently. The 2022 data, however, doesn't show a significant shift to other vessel classes. Small changes are visible like the increase in C4 vessels and the small increase in the BII-4l vessels. The smaller change in the vessel fleet may be due to the shorter period of drought and the lack of time for anticipation.

The lack of 6-barge convoys seems to cause the biggest disruptions for inland waterway transport and being able to cope with this loss will be a key factor in making the transport network more resilient to climate change. Being able to use the 6-barge convoys for part of the journey and being able to transfer cargo to different vessels or alternative modalities at transport hubs could be a solution to preventing large reductions in freight transport. Larger portions of the vessel fleet can still be deployed, ensuring better network capacity and less upward pressure on prices. Multiple solutions and mitigating measures should be implemented to work towards the 80% disruption-based availability.

In Table 5.12 and Table 5.13 the change in vessel fleet is shown for inland destinations laying further upstream than bottleneck Kaub. Here the barge convoys are already barely used in the baseline scenario and large Rhine vessels, M8 & M9, are more dominant. These hinterland destinations are used more for container transport and there isn't a visible shift to smaller vessel classes during the drought period in 2022. The only difference is that the average weight carried by the vessels in the dry period is roughly 60% of the weight carried in the baseline scenario.



(a)

(b)

Figure 5.4: The contribution of the separate vessel classes to the number of trips and transported weight (Vinke et al., 2022)

SK code	Trips	% Weight handled	Weight/Day (tonnes)
M8	5687	50,1%	9885,8
M9	1907	23,2%	4578,9
C3l	897	15,6%	3075,4
M11	602	3,5%	692,9
C4	297	2,3%	450,6
M6	284	1,6%	307,1
M12	185	1,6%	314,6
M10	96	0,9%	171,7
M5	63	0,3%	61,8
M7	39	0,3%	51,0

Table 5.12: passed Kaub vessel fleet baseline scenario

SK code	Trips	% Weight handled	Weight/Day (tonnes)
M8	345	44,4%	3334,3
M9	108	20,1%	1513,1
C3l	77	21,2%	1591,7
M11	24	3,1%	234,0
C4	20	4,5%	336,7
M6	19	1,5%	115,5
M7	10	1,1%	81,0
M12	9	1,5%	112,6
M10	7	0,7%	52,5
M5	7	0,7%	51,3

Table 5.13: passed Kaub vessel fleet drought scenario

5.3. Conclusion Data analysis

A method is created for quantifying a baseline scenario and a drought scenario based on available historical data of the recent droughts. The two scenarios are determined to enter into the transport model, along with the water levels corresponding to the bottlenecks for these scenarios. The baseline scenario corresponds to the period from November 2021 to June 2024, based on the available IVS next data. The drought scenario is set on the period from July to September 2022 and was determined based on the large number of days that critical water levels were measured during these months. The outcomes of the water levels and the water discharge corresponding to the average values during these periods are found in Table 5.1. For these water levels, the vessel capacities are determined using the van Koningsveld and Baart, 2020 model and Contargo, 2024. Following the transport data analysis, the vessel most frequently used for container transport from the Port of Rotterdam to the German and Swiss hinterland is the M8/V class large Rhine vessel. The vessel capacities used in the are shown in Table 5.14, which will determine the number of trips necessary to transport a certain amount of cargo. A maximum capacity of 208 TEU for the large Rhine vessel is used here based on Otten et al., 2017.

Area	loading capacity baseline	loading capacity drought
before Nijmegen	208 TEU	142 TEU
passed Nijmegen	208 TEU	120 TEU
passed Duisburg	167 TEU	101 TEU
passed Kaub	117 TEU	60 TEU

Table 5.14: Vessel capacity for Large Rhine vessel (M8) at all locations and scenarios

The transport data analysis also showed a reduction in transported cargo during the drought period. For all hinterland destinations, the freight transport was reduced by more than 50%, on average 54%. This was higher than the 20% objective from project CLARION, and to meet this goal, 43% of the baseline cargo transport via IWT would be handled by other modalities. For the container transport focused on the M8 design vessel, the cargo throughput must be increased with the values in Table 5.15 to meet the 80% operability for inland transport. The values are expressed in necessary weight per day to transship, necessary vessel arrivals per day where cargo needs to be handled, and the total design capacity of the hub on a yearly scale.

	weight / day	necessary M8 vessels / day	Yearly capacity hub
Nijmegen hub	558 tonnes	0,28	14.700 TEU
Duisburg Hub	1705 tonnes	1,03	44.933 TEU
Kaub hub	7357 tonnes	5,26	193.725 TEU

Table 5.15: Total necessary yearly capacity of the hub at different locations depending on the reduced freight transport behind the hub

The transport competition model developed is necessary to evaluate the cost-effectiveness of the transport hubs during a drought period, and the data analyzed will be used to simulate the different scenarios. Characteristics of the modeling scenarios are retrieved and only the exact locations of the transport hubs still need to be determined before starting to simulate the different scenarios. Retrieving reliable results for the hub locations will make the outcomes of the research method reliable and useful. Therefore, a method for finding suitable transport hub locations is described in the next Chapter.

6

Transport Hub Locations

In this chapter, the method for identifying suitable locations for cargo transshipment is shown and worked out. These locations will be integrated into the transport model and will be carefully determined to make the outcomes of the modeling scenarios reliable and practical for future use. As explained in the methodology chapter 3, the Best-Worst method is used to find the ideal locations for the potential transport hubs. First, the Best-Worst Method is explained, after which the search criteria and search methods for potential locations are defined. Potential locations are identified, and grading criteria for these potential locations are determined using existing literature and the outcome from the Best-Worst method workshop with experts from the port of Rotterdam.

The grades for different potential locations resulting from the BWM are calculated and shown in capacity-impact diagrams. After this definitive locations for the transport hubs before each bottleneck are chosen. It would be possible to choose multiple locations to accompany a large demand for transport transshipment before a bottleneck, but only 1 location is used per bottleneck in the transport model to simplify the simulations. The created method and the results of this chapter will give an answer to the fourth research question:

Which method can be used to identify suitable locations along the Rhine for transport hubs, considering existing infrastructure and accessibility to other transport modalities?

6.1. Best-Worst Method

The Best-Worst Method (BWM) is a multi-criteria decision-making (MCDM) method developed by Jafar Rezaei (Rezaei, 2015). According to BWM, the best (e.g. most desirable, most important) and the worst (e.g. least desirable, least important) criteria are identified first by the decision-maker. In this case, the decision-makers were experts working at the Port of Rotterdam. Pairwise comparisons are then conducted between each of these two criteria (best and worst) and the other criteria. The criteria are compared on a scale from 1 to 9, where a_{ij} shows the relevant preference of criterion i to criterion j. $a_{ij} = 1$, showing that the criteria are of the same importance, and 9 showing the extreme importance of i to j. After the Best and worst criterion is found the Best-to-Others, A_B, and Others-to-Worst vectors, A_W, can be determined:

$AB = (a_{B1}, a_{B2}, \ldots, a_{Bn})^T), AW = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$

A maximin problem is then formulated and solved to determine the weights of different criteria. The weights of the alternatives with respect to different criteria are obtained using the same process.

The optimal weight for the criteria is the one where, for each pair of $\frac{w_B}{w_j}$ and $\frac{w_j}{w_W}$, we have $\frac{w_B}{w_j} = a_{Bj}$ and $\frac{w_j}{w_W} = a_{jW}$. To satisfy these conditions for all j, we should find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j are minimized is formulated in the following model:

$$\min \max_j \left(\left| \frac{w_B^k}{w_j^k} - a_{Bj}^k \right|, \left| \frac{w_j^k}{w_W^k} - a_{jW}^k \right| \right) \tag{6.1}$$

subject to

$$\sum_{j=1}^{n} w_j^k = 1, \quad w_j > 0, \quad \forall j$$

The final scores of the criteria are determined by aggregating the weights from different sets of criteria and alternatives, based on which the best alternative is selected. A ratio for consistency is used for the BWM to check the reliability of the provided comparisons.

$$CR^k = \max_j \frac{\left| a_{Bj}^k \times a_{jW}^k - a_{BW}^k \right|}{a_{BW}^k \times a_{BW}^k - a_{BW}^k} \tag{6.2}$$

If the value of the Consistency ratio provided by expert k shown in Equation 6.2 are smaller than the consistency thresholds shown in Table 6.1, the judgments are consistent enough and acceptable (Liang et al., 2020). The comparison of the variables is fully consistent if for each j the values hold a_{Bj} x $a_{jW} = a_{BW}$, where a_{Bj} is the preference of the best criterion over criterion j, a_{jW} the preference of criterion j over the worst criterion, and a_{BW} the preference of the best criterion over the worst criterion.

Scales	**Criteria**						
	3	**4**	**5**	**6**	**7**	**8**	**9**
3	0,1667	0,1667	0,1667	0,1667	0,1667	0,1667	0,1667
4	0,1121	0,1529	0,1898	0,2206	0,2527	0,2577	0,2683
5	0,1354	0,1994	0,2306	0,2546	0,2716	0,2844	0,2960
6	0,1330	0,1990	0,2643	0,3044	0,3144	0,3221	0,3262
7	0,1294	0,2457	0,2819	0,3029	0,3144	0,3251	0,3403
8	0,1309	0,2521	0,2958	0,3154	0,3408	0,3620	0,3657
9	0,1359	0,2681	0,3062	0,3337	0,3517	0,3620	0,3662
a. The thresholds for the combinations with 2-scale should be 0.							

Table 6.1: Thresholds for Different Consistency Ratios and Number of Criteria (Liang et al., 2020)

The complete Best-Worst Method used in this research is put in Appendix C along with the results from various experts from the Port of Rotterdam.

6.2. Boundary criteria and search methods

To set boundaries on the minimum size of the terminal, the BCTN inland terminals are considered, and the smallest terminal is chosen to be the minimum size for the potential transport hub (BCTN, 2024). This terminal operates with 1 crane and 1 quay wall to accommodate all inland vessels and is located in Roermond. The terminal quay wall facilitates enough mooring room for 1 inland vessel to stay at the terminal (maximum vessel of 140 meters, ITB, 2024). To save costs and avoid large-scale construction, the potential site must contain existing infrastructure or be adjacent to existing infrastructure. The location may, therefore, not be located in an undeveloped location where the construction of a hub would be drastic. There must also be at least a connection to another modality from the location to guarantee multi-modality without extreme interventions in the landscape, and the most important criterion is that the location of the potential transport hub is before the navigable threshold. The main criteria with this minimum design terminal are then as follows:

- Minimum 140 m quay walls (to accommodate 1 maximum size inland vessel)
- Connection to road or rail network

- Minimum surface area 10.000m^2 (capacity 30.000 TEU per year, BCTN, 2024)
- Existing infrastructure or adjacent to existing infrastructure
- Located before the navigable threshold that causes the bottleneck.

Using the following programs and resources, potential locations are identified and outlined:

- Route Scanner
- Google Maps
- Rhein Radar Atlas (Karmineke, 2007)
- Digital twin port of Rotterdam
- Overpass Turbo

This will help identify potential bottleneck locations, which will then be further investigated using the Best-Worst Method. The same methods used to identify the locations can also be used to identify their characteristics. To rank these locations, grading criteria must first be established to determine the ideal location.

6.3. Grading criteria

From Tadić et al., 2019, inputs and outputs were derived for terminal efficiency evaluations. Quay length, number of handling equipment, terminal area, maximum draught, throughput capacity, and storage capacity were found to be the most used inputs and outputs for investigated evaluations. The size of terminals was categorized into 4 different sections, small, medium, large, and very large, with boundaries of 100.000, 200.000, and 400.000 TEU per year. Liang et al., 2021, investigated a Best-Worst method for a new terminal location. Here the terminal would be newly constructed instead of using old infrastructure preferred in this research. Investment costs would be divided into land purchase costs, construction costs, and other investment costs. The environmental effects are addressed along with the impact of the terminal on the transport infrastructure and economic development. The transport networks are also addressed by looking at the present infrastructure at locations and the current competition on the existing networks. If a railway line is present, it could be a big advantage, but if this railway is already at its maximum capacity, it won't be of much use without extra investments into the infrastructure. Consulting the experts at the port of Rotterdam, the operational costs are added as a criterion and added with the investment costs. The combined criterion is called the business case for the transport hub.

All locations are stored in a database, which includes their properties and capacities. These locations are then categorized based on their capacity and the assigned grade. This categorization helps in prioritizing locations for development, ensuring that the most feasible and cost-effective sites are identified first. The locations will be graded on the following characteristics derived from the aforementioned literature:

- Handling capacity - number of berths and cranes to handle cargo
- Storage capacity - facilitate storage when the low water levels cause congestion
- Quay length - number of vessels able to more
- Business case - land purchase, construction, other investments, and operational costs based on the size of the hub.
- Environmental effects - Effects of inland terminal(-related) operations on the environment, e.g. release of hazardous materials or emissions in surroundings.
- impact on local residents - regional traffic congestion/competition, nuisance from the terminal, and economic development
- Access to road networks - transport infrastructure and regional traffic competition
- Access to railway network - rail infrastructure and traffic competition

The worked-out Best-Worst Method is put in Appendix C, and the final weights for each criterion are shown in Table 6.2. Now only the grading for each criterion needs to be determined to find the most efficient location for the transport hub.

	Handling capacity	**Storage capacity**	**Quay Length**	**Business case**
Weights	0,211	0,117	0,082	0,260
	Environmental effects	**Local residents**	**Road access**	**Rail access**
Weights	0,085	0,057	0,034	0,154

Table 6.2: Weights for Various Criteria

6.4. Grading methods alternative criteria

For each weighted criterion, a grade must be assigned to determine the most efficient location for the transport hubs. A specific method will be developed for grading each location based on these weighted criteria. To facilitate this grading process, scales will be introduced, which will also be validated by the experts who provided insights on the BWM. The scoring for each criterion will range from 1 (indicating poor performance) to 5 (indicating excellent performance).

6.4.1. Handling Capacity

The grade for the location based on its handling capacity will be based on the number of operating berths where cargo can be transshipped. The minimum is 1 operating crane and the maximum grade is for 3 operating berths with a crane. This is also the minimum and maximum for the BCTN inland terminals, which result in a small terminal, < 100.000 TEU, and a very large terminal, > 400.000 TEU.

operating berths	1	2	3
grade	1	3	5

Table 6.3: Grading handling capacity

6.4.2. Storage capacity

The grade for the storage capacity will be determined by the surface area of the terminal. The area sizes are determined by looking at the BCTN terminals, where 10.000m^2 is the smallest terminal (BCTN Roermond), and larger than 100.000m^2 holds the largest terminal, which is associated with a very large terminal (BCTN Meerhout). The other boundaries are determined by looking at the other terminals. Beringen is still small, with an area of 20.000m^2 with 50.000 TEU per year, and at 30.000m^2, the terminal can already be off medium capacity. Therefore, the second boundary is taken at 25.000m^2, and because a terminal with an area of 45.000m^2 is almost at large capacity, the third boundary is at 40.000m^2. The last boundary at 65.000m^2 is not taken linearly because the terminal size, large to very large, also doesn't go linearly.

surface area (m^2)	10.000-25.000	25.000-40.000	40.000-65.000	65.000-100.000	100.000 +
grade	1	2	3	4	5

Table 6.4: Grading Storage capacity

6.4.3. Quay Length

The grading of quay length is determined by the number of vessels able to move at the terminal. The minimum number of vessels is 1 with one operating berth. The maximum number of operating berths is 3, and for each of these berths, an extra mooring location is designed for a vessel waiting in line. The grades are then as shown in Table 6.5. The total quay length is determined as the number of vessels times 140 meters for the designed vessel.

number of vessels able to more	1	2	3	4	5
grade	1	2	3	4	5

Table 6.5: Grading quay length

6.4.4. Business case

To determine a grade based on the business case required per location, the existing infrastructure at the location is examined. 4 investments are taken separately here, and for each investment required, a number will be deducted from the grade per investment. The quay wall investment is to lay a quay length for 1 extra vessel to more, the foundation investment is per 10.000m^2, buying out the owner present at the terminal can cause a lot of trouble and will cost 1 number in the grade, and the investment for the operating crane is determined to increase handling capacity. In this way, if a location is picked where the owner needs to be bought out, the foundation for 40.000m^2 is planned along with room for 4 vessels and 2 operating berths; the grade will be 1. Because lower than 1 isn't possible, this is the maximum investment that can be done per terminal.

The operational costs for the potential location need to be determined to complete the business case of the location. Making the transport hub cost-effective in terms of operating costs depends on the size of the hub. A small hub is hard to make cost-effective, as came forward in the Best-Worst Method workshop with experts. A large hub, on the other hand, has lower operating costs per TEU and is, therefore, better for the business case. The implementation of the operational costs into the transport hub will be -1 for a small hub, +0,5 for a large hub, and +1 for a very large hub.

investment	quay wall	foundation	buy out owner	operating crane	hub size
grade	-0,5	-0,25	-1	-0,5	-1,+0,5,+1

Table 6.6: Grading Investment costs

6.4.5. Environmental effects

1 point is deducted for each aspect that applies to the location: Close to a protected environment, constructing the terminal at a green field location, and the size of the terminal. The size of the terminal will increase the water, air, and noise pollution and, therefore, is an important factor.

effect	Close to protected environment	green field location	medium	large	extra large
grade	-1	-1	-1	-2	-3

Table 6.7: Grading environmental effects

6.4.6. Impact on local residents

For each impact on the residents, the grade is deducted by 1, except for being bought out of their homes because that will take a lot of effort if necessary. The other impacts on the local residents are noise pollution, traffic congestion, and horizon pollution.

impact	bought out home	noise pollution	traffic congestion	horizon pollution
grade	-2	-1	-1	-1

Table 6.8: Grading impact on local residents

6.4.7. Access to road

The grade of the road access is determined by the size of the road network connected to the terminal. The terminal can be easily connected to a highway, to a provincial road or only be connected by a village road. The connection is determined by a maximum radius of 2 km to consider a road nearby. This is around the same distance the highway at Valburg would have to the rail terminal Gelderland. The size of the road is determined by the speed limit for each type of road in the Netherlands (112schade.nl, 2024). Higher speed limits allowed in Germany will be graded a 5 as well.

speed limit km/h	30	50	60	80	100
grade	1	2	3	4	5

Table 6.9: Grading Road access in km/h

6.4.8. Access to rail

The accessibility of the terminal via rail is determined by two factors: if the terminal is connected at all to a railway network and if this railway network has the potential capacity to handle extra cargo on short time notice. The railway line should be accessible from the terminal to prevent extra transport in between using trucks.

rail access	no access	Access with no capacity	Access with capacity
grade	1	3	5

Table 6.10: Grading Railway access

6.5. Capacity-Impact diagram

The grades of the potential locations will be plotted on the capacity-grading diagram shown in Figure 6.1, where the locations with the highest grade based on the weighted criteria are plotted on the right side of the graph. The capacity depicts the potential size of the transport hub at a certain location and how much cargo can be transported via this location. The capacity of each location will be stated as mentioned above as small, medium, large, and very large for respectively the boundaries of 100.000, 200.000, and 400.000 TEU per year capacity (Tadić et al., 2019). Locations have different possibilities for size and impact depending on the design and the necessary cargo throughput. Therefore, a visualization in this graph paints a picture of how all the locations are divided, and locations can be implemented as lines instead of points when different sizes are possible. The cargo throughput that needs to be handled by the transport hub will be determined by a data analysis investigating the IVS Next data.

The existing infrastructure at potential locations is expected to be used by half of the capacity. This is due to the already existing cargo throughput that needs to be taken into account and the potential for increasing this capacity during periods of drought. To increase the handling capacity, the operating hours of these locations are expected to increase during periods of drought.

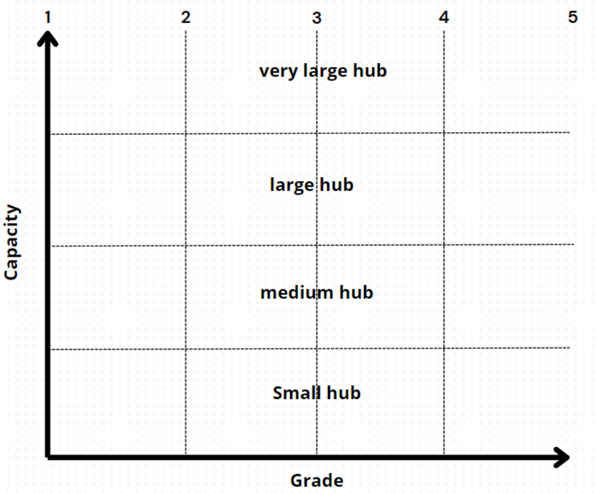


Figure 6.1: Capacity-Grading chart

6.6. Transport hub location Nijmegen

As described in subsection 3.1.3, the hard layer at Nijmegen forms problems with the water level and is the first bottleneck traveling from the Port of Rotterdam to Basel. The port of Nijmegen is located in Nijmegen and already handles large cargo numbers each year and helps connect the Port of Rotterdam to the German hinterland. To accompany the criteria described, the locations before the bottleneck are found between Ochten and the Oversteek bridge in Nijmegen. Finding locations closer to the port of Rotterdam will make less sense due to the small distance traveled up to this point. Finding locations beyond the bridge will already reach the hard layer and thus decrease sailing depth.

Using the boundary criteria and search methods, 10 locations are found along the waterway in the designated area for the hub, where there is some space for a terminal. Based on the location's characteristics and potential, each criterion is graded, and the final grade is shown in Table 6.11. As mentioned in the methodology, the existing infrastructure at operating terminals will be counted as half of the entire capacity of the terminal, as well as the impact on local residents and the environment. The full grading table is shown in Appendix D and the capacity grading diagram is shown in Figure 6.2. The top 3 potential locations score pretty similar to each other and outperform the other locations by a large factor. The 7 other locations score significantly worse due to the limited infrastructure available at these locations and the larger impact of these locations on the local residents and the environment. 3 alternatives are still considered and looked at individually.

location	size	grade	function
Noordkanaalhaven	medium - extra large	2,73 - 3,09	Old port
BCTN Nijmegen	small - large	2,38 - 2,76	Port
Port of Nijmgen	medium	2,73	Port
Railterminal Gelderland Valburg	small	2,47	Potential Hub
De Beijer Groep Dodewaard (next to)	medium - large	2,27 - 2,35	Empty space
Druten Wijgula B.V.	medium	2,21	Ship reparations
Deelens transport Waalbandijk	small	2,10	Industry
Ravestein B.V. Deest (next to)	large	2,09	Empty space
River Harbour Waalbandijk	medium	2,04	Rivier cruise harbor
Ijzendoorn	medium	1,86	Ship rest station

Table 6.11: Grades and sizes potential locations Nijmegen

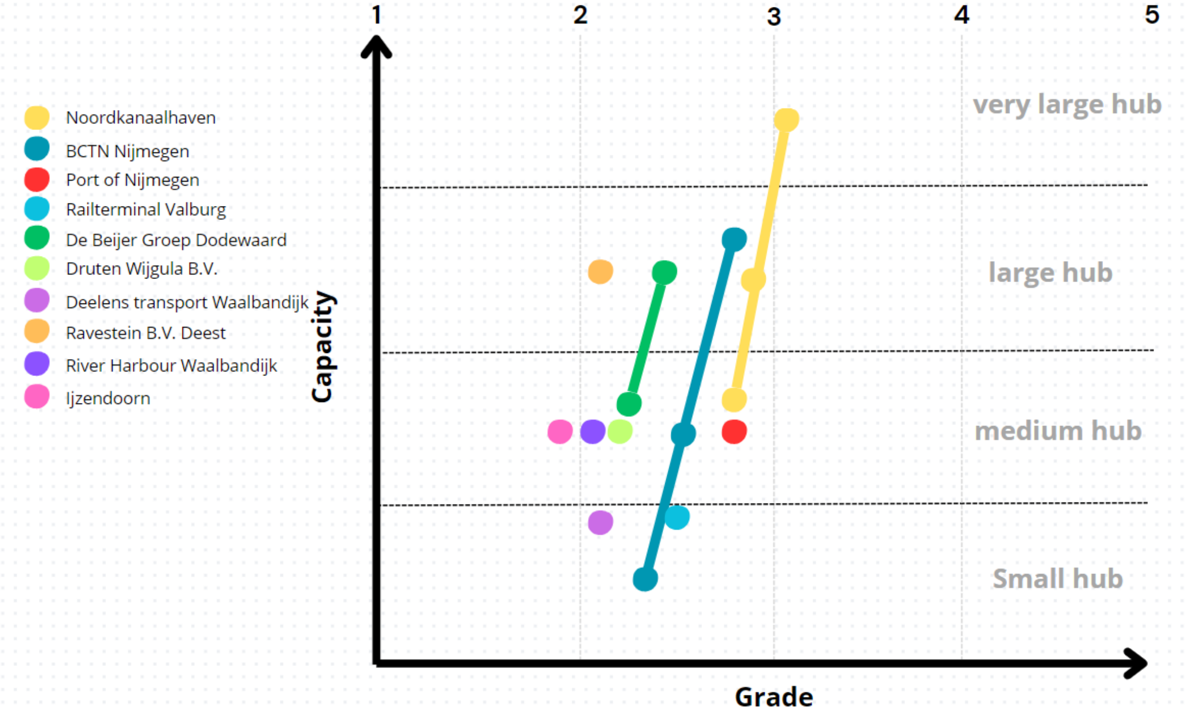


Figure 6.2: Capacity Grading diagram for the potential locations at Nijmegen

The Port of Nijmegen is identified as a viable option through the Best-Worst Method. However, there are two key challenges in converting this location into a transport hub. First, the port is already operating at full capacity, and space would need to be created by relocating other companies. This would require significant effort and expense, with limited space likely to be freed up. The second issue is that the port is situated behind the Weurt lock, leading to additional travel time when transshipping goods in Nijmegen.

The other two options are similar and primarily focus on utilizing the area around the Noordkanaalhaven for the transport hub. Option 2 involves expanding the BCTN terminal in Nijmegen, where different sizes of the hub are possible. In this case, the quay wall of the terminal would be extended, and by increasing terminal capacity, more freight could be handled. The surrounding area of Noordkanaalhaven could then be used for additional storage.

Option 3 proposes building a new terminal in the Noordkanaalhaven, where available space and existing quay walls, once used by a former power station, make it an ideal location. Since the site is currently vacant and contains much of the necessary infrastructure, it is well-suited for a transport hub. Additionally, there would be no conflicts with the existing operations at the BCTN terminal, making this location the ideal choice for the transport hub in Nijmegen.

6.7. Transport hub location Duisburg

As explained in subsection 3.1.4, the issues with water depth during drought periods occur just beyond Duisburg. This results in reduced loading capacity for vessels and additional low-water surcharges imposed by barging companies. Despite this, Duisport remains the largest hinterland port, playing a crucial role in connecting the Port of Rotterdam with Germany's industrial heartland. Duisport already boasts advanced infrastructure and excellent connections to road and rail transport. With a wide range of terminals handling container cargo, dry bulk, and liquid bulk, selecting a greenfield location in Duisburg seems illogical and not economical.

The area looked at in Duisburg is from Walsum to the Krefeld-Uerdinger Brücke upstream. This area contains all the major Duisport terminals and holds great access to other modalities. Choosing a location more downstream will decrease the economic benefit of transshipment at Duisburg and choosing an area upstream will already increase sailing problems at low water levels. 11 locations are found in this area and are graded with the BWM, and the results are shown in Table 6.12. 3 locations have different potentials when it comes to the size of the transport hubs, but most locations will be created by increasing operating hours at existing terminals.

location	size	grade	function
Duisburg Gateway Terminal (DGT)	medium - extra large	3,84 - 4,09	Empty Port terrain
Duisburg Intermodal Terminal (DIT)	medium	3,34	Terminal
Hutchison Ports DeCeTe Duisburg	medium	3,22	Terminal
Rhein Ruhr Terminal (Home Terminal)	medium	3,22	Terminal
HGK Intermodal GmbH (Gateway West)	medium	3,03	Terminal
Homberg	medium - large	2,98 - 3,06	Empty Port terrain
DUSS-Terminal Duisburg-Ruhrort Hafen	medium	3,00	Terminal
Sudhafen Duisburg	medium	3,00	Terminal
Duisburg Trimodal Terminal (D3T)	medium	2,95	Terminal
Multimodal Terminal Duisburg (MTD)	small - medium	2,56 - 2,79	Terminal
Nordhafen Walsum	small	2,62	Dry bulk terminal

Table 6.12: Grades and sizes potential locations Duisburg

Most of the grades resulting from the BWM turned out to be higher than those in Nijmegen. This is mostly due to the fact that most of the locations already boast existing terminal infrastructure, and the railway access in Duisburg is further developed. In contrast, the railway access in Nijmegen was barely present. Figure D.2 shows the visual representation of the grades of each location, and one location comes out on top. Duisburg Gateway Terminal (DGT) has the highest grading for each potential size (depending on the cargo throughput) and even scores the best for all locations looked at each bottleneck. This is because the DGT is centrally located within the Port of Duisburg, offering good rail and road transport connections. Although this section of the port is still undeveloped, it already has the foundations for storage and quay walls in place. The area is large enough to accommodate any terminal size, including extra-large facilities, making it an ideal choice for the transport hub in Duisburg.

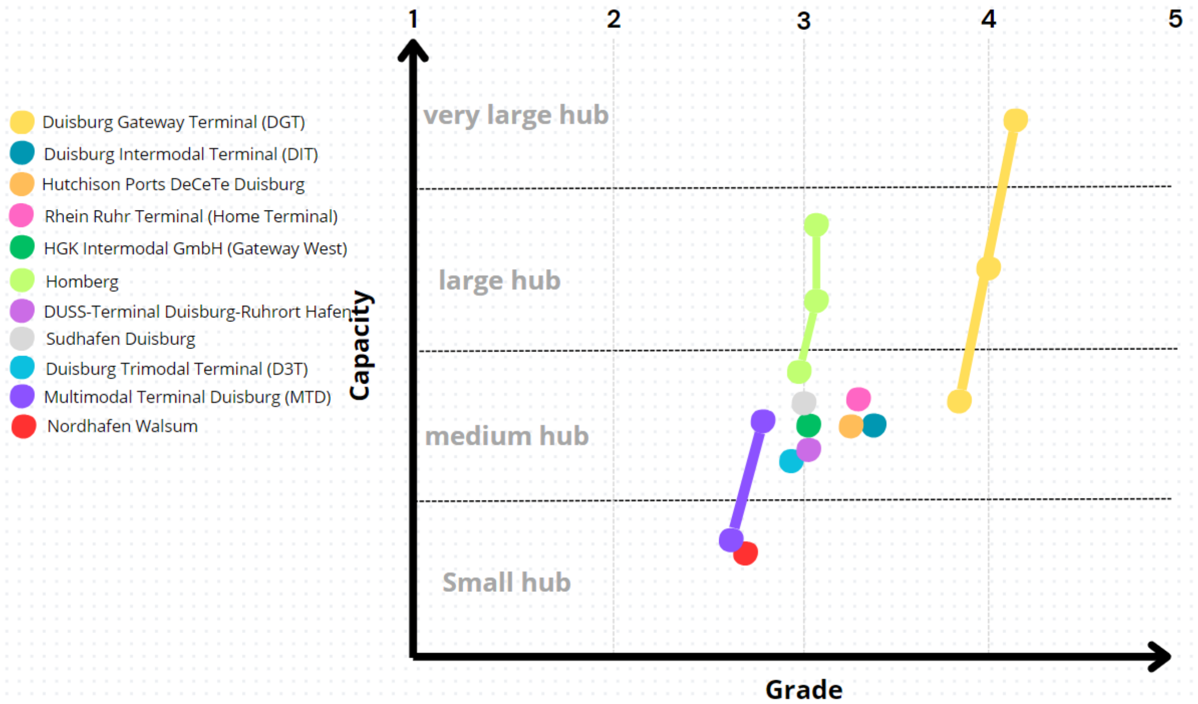


Figure 6.3: Capacity Grading diagram for the potential locations at Duisburg

6.8. Transport hub location before bottleneck Kaub

The bottleneck at Kaub turned out to be the major problem for IWT during periods of drought. Loading rates were drastically reduced to be able to pass the navigable threshold, or, at times, it wasn't even possible to pass carrying cargo. Large parts of Germany couldn't be reached by water, and Swiss hinterland ports also needed to look for an alternative form of cargo transport. The area just before Kaub presents challenges for development due to its hilly terrain. There is limited infrastructure in place, and natural water inlets suitable for terminal construction are scarce. For this reason, a broader area was examined, stretching from Kaub upstream to Andernach downstream, to identify multiple potential locations for the transport hub. This area includes some existing terminals and infrastructure, along with several potential water inlets suitable for development. The grades for these potential locations, shown in Table 6.13, are generally lower than those in Nijmegen and Duisburg, primarily due to the limited infrastructure and fewer buildable areas along the river in this region. That is why drastic measures are needed at many of the locations to construct a new terminal. This mainly involves hindrances to the environment and residents or the relocation of companies at existing terminals. The worst 5 locations shown in Figure 6.4 are locations with lots of nuisance to residents or close to greenfield locations. Major interventions need to be done here to then only have a small or medium hub left. The other locations offer more possibilities and are therefore compared to choose the ideal location.

location	size	grade	function
(H&S) Haeger & Schmidt Logistics Andernach	small - medium	2,74 - 2,93	Terminal
Lahnstein	small - medium	2,65 - 2,85	Industry with quay walls
Vallendar bahnhof	small - large	2,21 - 2,5	Waterside railway station
Contargo Koblenz	small	2,31	Container terminal
Rhein Marina Kaiser Wilhelm	small	2,04	Bay
Im sandchen Koblenz	small - medium	1,69 - 1,94	Waterside open area
Rhein Lache Koblenz	small - medium	1,68 - 1,89	Small yacht club
Koblenz Raptors	medium	1,7	Baseball stadium
Hafenstrabe koblenz	medium	1,58	Small port

Table 6.13: Capacity Grading diagram for the potential locations at Kaub

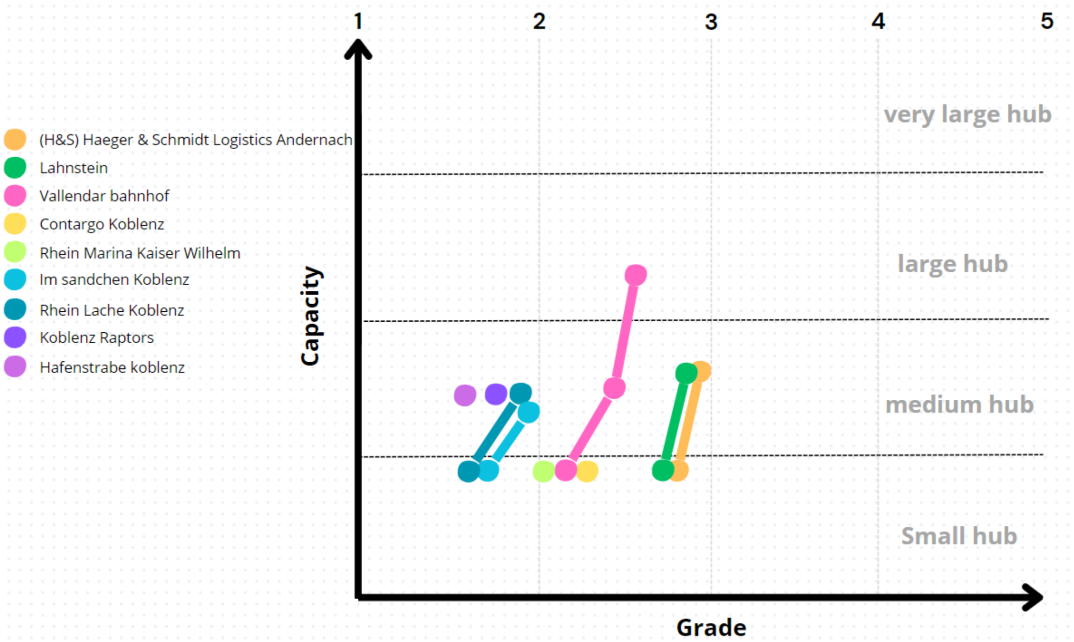


Figure 6.4: Capacity Grading diagram for the potential locations at Kaub

Lahnstein and Vallendar Bahnhof are two locations where a new terminal needs to be constructed, but the location is promising when it comes to road and rail connections. Lahnstein is a small river inlet where it is possible to construct a medium-sized terminal connected to a railway line. The location is, however, in an area prone to lower water levels because it lies beyond Koblenz, where the water level drops slightly. Vallendar Bahnhof is a riverside train station with some available area to construct a terminal. It is, however, hard to put any infrastructure in place, and parking spaces need to be relocated to make room for the terminal.

The other two potential locations are existing inland terminals with small rail access and decent road access. Around the Contargo terminal, it is quite packed, and the only possibility for modality changes is during extended operating hours. Therefore, there is only room for a small hub. At the terminal in Andernach, there is more space available, allowing for the development of a larger terminal. Considering the degree of intervention required for each terminal, the Haeger & Schmidt terminal is chosen as the location for the transport hub.

6.9. Conclusion transport hub location analysis

Using the Best-Worst Method to identify suitable locations for future transport hubs before the bottlenecks has yielded useful and realistic outcomes. A few assumptions and simplifications need to be made when grading potential locations, but these are addressed when picking a definitive location for the hubs. Future research should incorporate the availability of sites and upcoming planning for these locations to enhance the method for finding suitable transport hub locations.

The ideal locations for the transport hubs along the Rhine were determined to be at the Noordkanaalhaven in Nijmegen, the Duisburg Gateway Terminal, and H & S logistics in Andernach just before Koblenz. Different sizes are possible for the locations depending on the required capacity of the transport hub. For Nijmegen, this means a medium, large, or extra-large hub with respectively 150.000 TEU, 300.000 TEU, and 400.000 TEU yearly capacity following an average of the standard terminal sizes. The same calls for Duisburg, and for Kaub, a small hub is also possible with an assumed capacity of 50.000 TEU. Using insights from the data analysis (Table 5.15), a small hub at Nijmegen and medium hubs before Duisburg and Kaub would result in the most efficient solution.

Simulating the scenarios will determine the cost-effectiveness of the different hubs and will point out the ideal location of the hub that has the biggest effect on the transport network. After the results are retrieved the definitive capacities of the hubs can be determined.

7

Results

In this chapter, the results of the developed transport competition model are shown for each scenario using input retrieved in the previous chapters. The baseline scenario is modeled to provide an accurate representation of the competitive transport network in Northwestern Europe, and the drought scenario will show the increase in IWT costs. Although an unlimited number of seaports are possible, only the ports of Rotterdam, Hamburg, and Antwerp are added to the model to simplify the calculations. Disruptions in the network are simulated as accurately as possible, allowing for reliable results and an answer to the fifth research question:

How will these modality changes at the transport hubs affect the total transport costs of the cargo compared to 1 modality transport for the same destination?

7.1. Baseline scenario

7.1.1. Outline NUTS regions

The area considered will spread over the Netherlands, Germany, Belgium, Switzerland, Austria, The Czech Republic, and parts of Poland, Italy, Slovakia and France. These are areas where the port of Rotterdam is active or which form interesting destinations to reach via IWT. Other seaports, except for Rotterdam, Hamburg, and Antwerp, are not yet considered in this scenario. The area is shown in Figure 7.1 for which the inland waterways, terminals, ports, and railways are filtered. More southern regions are not of interest due to the presence of large ports such as Marseille, Genoa, Venice, Trieste, and Koper. Further east, there are also major ports like Szczecin and Gdansk. Additionally, the area in France is complicated by the ports of Dunkirk and Le Havre."

Figure 7.1: Definitive Outline NUTS regions used for all simulations

7.1.2. Output contested hinterland regions per seaport

The results of the baseline scenario are shown in Figure 7.2 where most of the areas won by the port of Rotterdam are along the inland waterways, and the other further destinations are won by Hamburg rail or Antwerp rail transport. 259 NUTS regions are won by Rotterdam, 117 by Antwerp, and 248 by Hamburg.

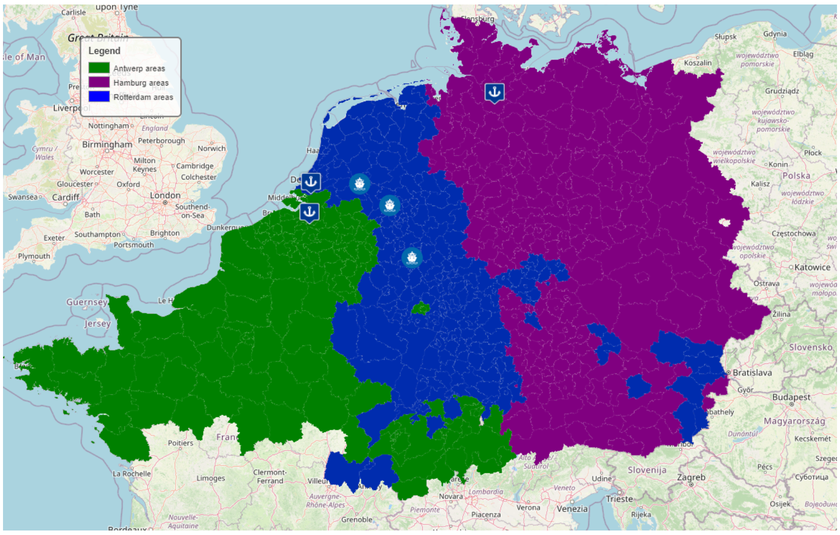


Figure 7.2: Results Baseline Scenario

Figure 7.3 and Figure 7.4 show the difference in price for transport from the cheapest seaport compared to the transport price of the second cheapest seaport. The areas won by the port of Rotterdam are not much cheaper than the other seaports, but this is mainly due to the nearby location of the port of Antwerp, which is easily connected to the same shipping network as the port of Rotterdam. In Figure 7.4, the color scheme is zoomed in on smaller differences to better show the contrast of pricing in the hinterland where the competition is close between seaports. If transport would cost €60.000 from the port of Rotterdam and the second cheapest option would be €100.000 from the port of Antwerp the percentage shown in the Figures would be 40%, because it's 40% cheaper to transport to this destination from the port of Rotterdam than the port of Antwerp.

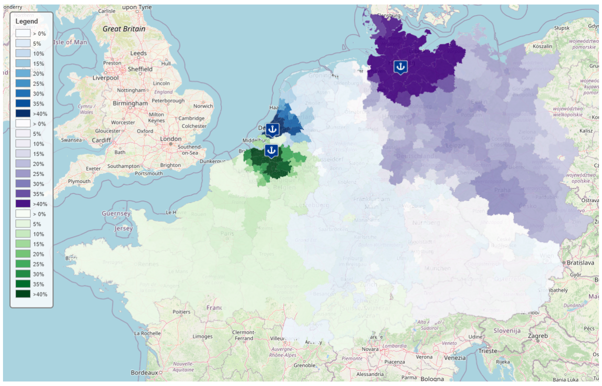


Figure 7.3: Percentage of contested areas being cheaper than other seaports

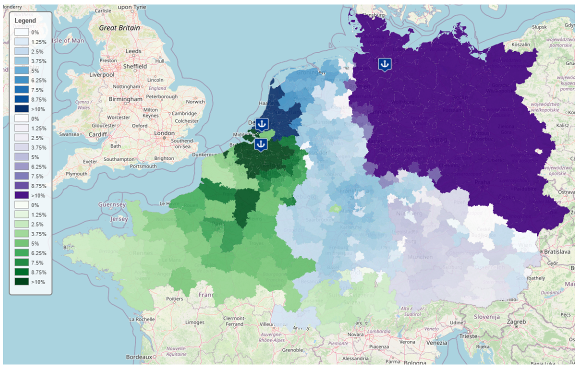


Figure 7.4: Percentage of contested areas being cheaper than other seaports, 10% maximum difference to increase perspective in hinterland

7.1.3. Modality share per seaport and modality

The modality share for the different seaports in the hinterland areas are shown in Figure 7.5, Figure 7.8, and Figure 7.9 for respectively Rotterdam, Hamburg, and Antwerp. Visible is that rail transport from the port of Rotterdam is never the cheapest mode of transportation towards a hinterland region. Figure 7.6 shows the price for transporting 1000 TEU from the port of Rotterdam towards a hinterland destination.

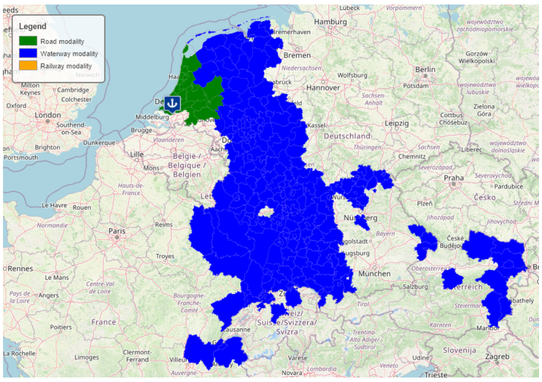


Figure 7.5: Modality share Rotterdam

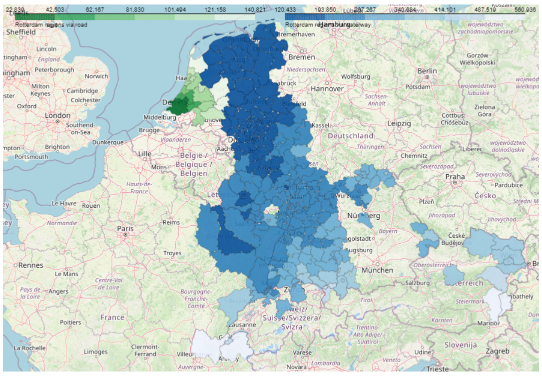


Figure 7.6: Pricing modality share Rotterdam for 1000 TEU

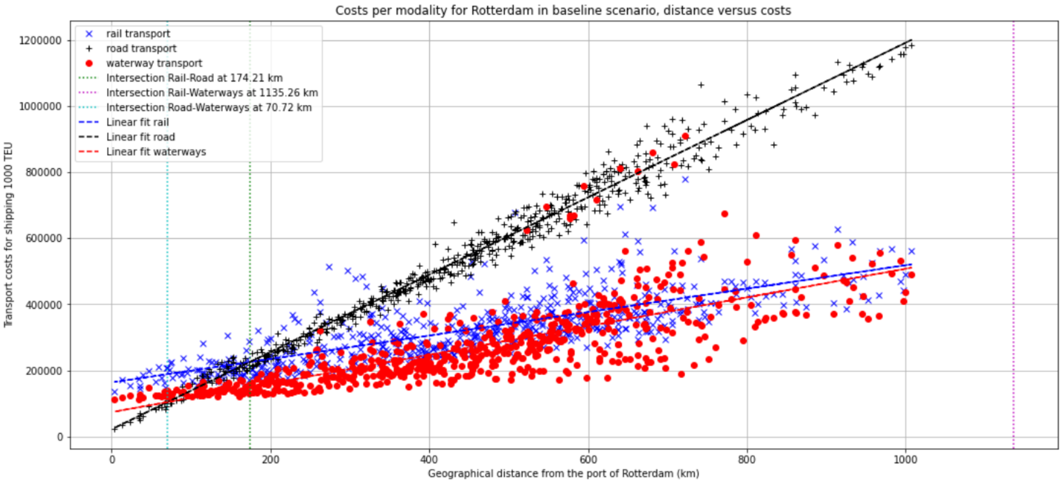


Figure 7.7: Modality spread port of Rotterdam basecase scenario

The closest region won by IWT has a transport cost of €120.433, and the furthest region in France is priced at €560.936 for IWT. Rail transport towards the hinterland is more dominant for the ports of Hamburg and Antwerp. For the port of Rotterdam, all destinations are plotted in Figure 7.7 to show the transport prices per modality for geographical distances from Rotterdam. For this scenario, IWT was cheapest for 518 destinations, 25 destinations for road transport, and 81 destinations for rail. A linear fit is created for all the destinations to find the correlation between geographical distance and costs. It is visible that road transport is, on average, the cheapest means of transport for nearby transport to 70 km, IWT for intermediate transport to 1135 km, and rail for transport to far away.

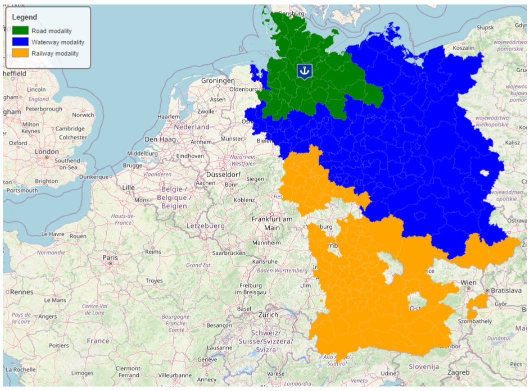


Figure 7.8: Modality share Hamburg

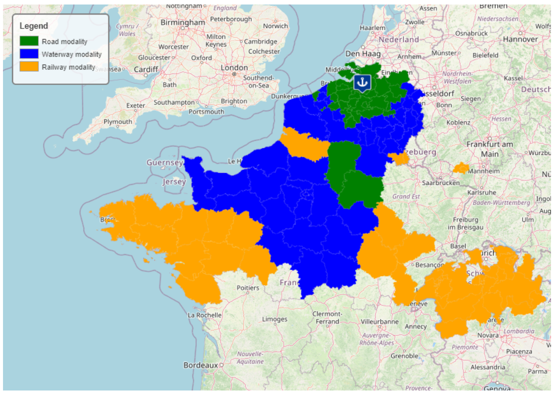


Figure 7.9: Modality share Antwerp

7.2. Drought scenario

7.2.1. Output contested hinterland regions per seaport drought scenario

During periods of drought, the number of contested areas won by the port of Rotterdam has been reduced to 106 (59% loss). The port of Hamburg gained 57 areas, and Antwerp won 213 areas, which is an 82% improvement of the baseline scenario. The large area losses in the middle of North-Western Europe are visible in Figure 7.10, where the port of Rotterdam is no longer a contender for the hinterland regions. Figure 7.11 and Figure 7.12 show the withdrawal of competitive advantage during a drought period for the port of Rotterdam. Only the Moesel is still the cheapest route for hinterland destinations via IWT from Rotterdam. Areas around Duisburg are still roughly 5% cheaper than the other seaports and show no decline between the two scenarios competition-wise.

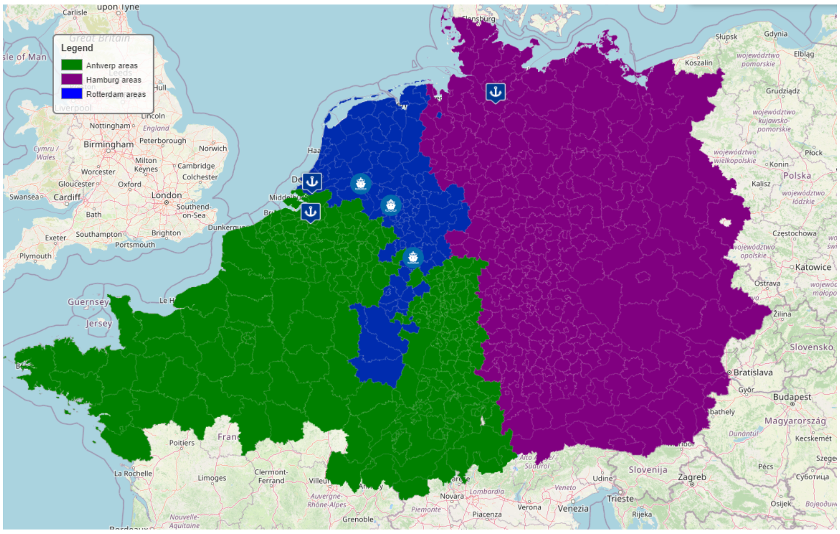


Figure 7.10: Results drought Scenario

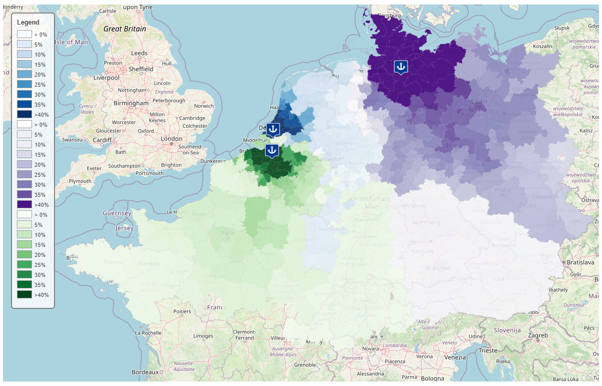


Figure 7.11: Percentage of contested areas being cheaper than other seaports in dry periods

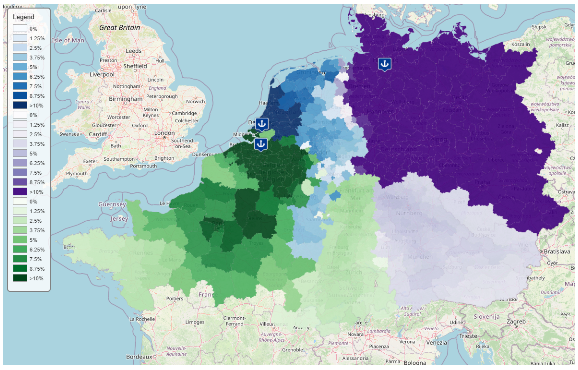


Figure 7.12: Percentage of contested areas being cheaper than other seaports, 10% maximum difference to increase perspective in hinterland

7.2.2. Difference between baseline and drought scenario

The difference between both scenarios for the port of Rotterdam is shown in Figure 7.13. The increase in price for the cheapest mode of transport for shipping 1000 TEU to a hinterland destination is shown in red gradations. Hinterland destinations past Kaub, which don't have a railway connection nearby, are the locations with the highest price increase. This increase is the most extreme in Göppingen, with a 47% increase in transport cost for the same shipment during the baseline scenario. The white areas in the figure are areas that already had another favored modality in the baseline scenario. Because there's no price increase for road or rail transport, the areas remain the same and have no price increase.

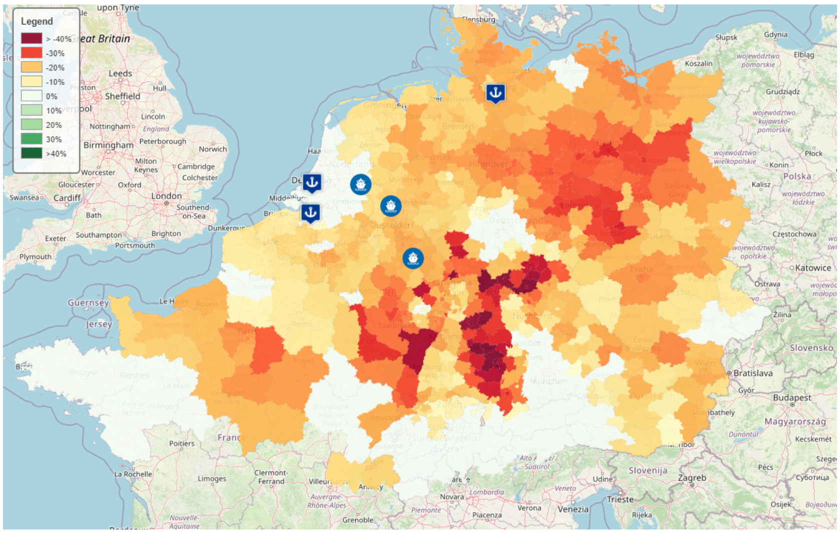


Figure 7.13: Percentage of increase in transport price from the port of Rotterdam during the drought scenario

7.2.3. Modality share drought scenario for the port of Rotterdam

The reduced modality share of 59% for the port of Rotterdam is visible in Figure 7.14. The lost areas are won by rail transport from Antwerp and Hamburg, which are not affected by low water levels. The new prices in the Rotterdam hinterland areas are shown in Figure 7.15. More outputs of the model are created for the ports of Antwerp and Hamburg, but to limit the length of the results, they are put in Appendix E. In

For all hinterland destinations, the modality spread from the port of Rotterdam is plotted again in Figure 7.16. Here, IWT is less favored for the NUTS regions, and for only 279 destinations, IWT is the cheapest modality. 27 destinations can be reached via road transport, and 318 locations via rail transport. Another linear fit is created to show the different correlation between geographical distance and transport costs during the drought scenario. The distance where rail transport is cheapest has reduced from 1135 km to 371 km. The decrease in distance, where road transport is the cheapest, is mostly due to the new linear fit, which is now 52 km.

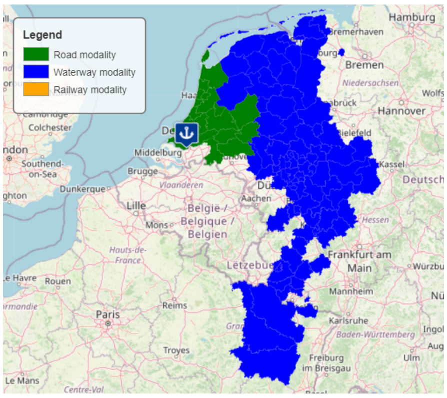


Figure 7.14: Reduced modality share Rotterdam during drought scenario

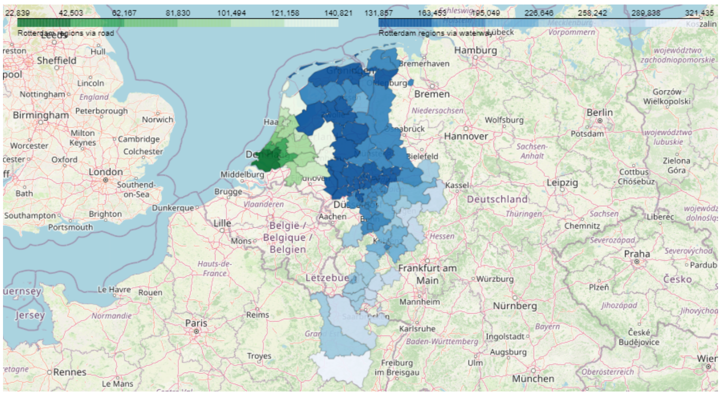


Figure 7.15: Pricing modality share Rotterdam for 1000 TEU during drought scenario

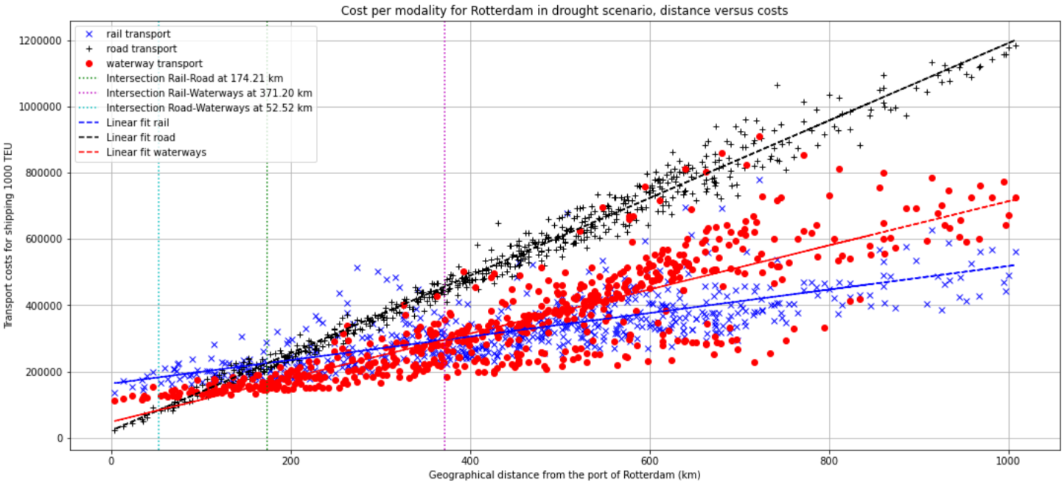


Figure 7.16: Modality spread port of Rotterdam, drought scenario

7.3. Drought scenario with integrated transport hubs

7.3.1. Output contested hinterland regions with the implementation of transport hubs

The implementation of the transport hubs aims to prevent the large-scale decrease of loss of hinterland regions, where the port of Rotterdam is no longer the favored seaport for hinterland freight transport. Transport hubs could reduce transport costs by working more efficiently with the available water levels and different modalities. Each transport hub is looked at separately without using multiple hubs for 1 hinterland destination. In this way, NUTS regions can be found for which the distinctive transport hub is an efficient alternative when it comes to transport costs. The transport hubs are also considered when only IWT is possible, and there is no alternative transport. Hereby, the effect of the hubs on IWT is found. As explained in subsection 4.4.2, first, the impact of transport hubs with a transshipment fee of €90 and €50 per TEU are simulated to see which areas from the implementation of one of the 3 transport hubs. For the €90 transport hubs, the results are shown in Figure 7.17, and for the €50 transport hubs, the results are shown in Figure 7.18. For both scenarios, 7 NUTS regions are won by traveling via Kaub, where 3 were previously cheapest via Antwerp and 1 via Hamburg. Duisburg won 1 region, but this was already won by the port of Rotterdam, and Nijmegen is, for 0 regions, the cheapest transport alternative.

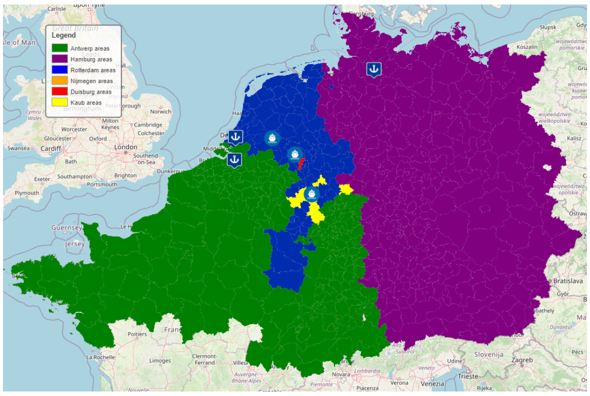


Figure 7.17: Results transport hub scenario, with €90 transshipment costs per TEU

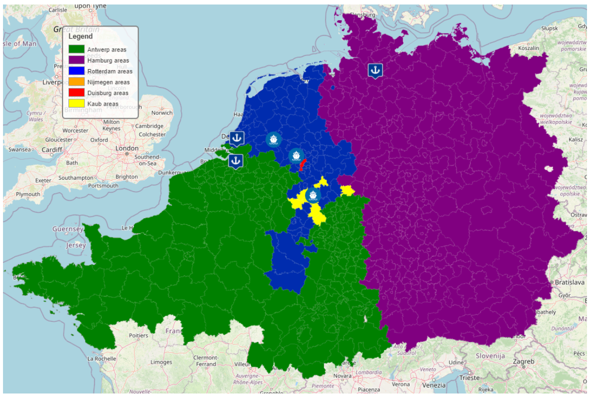


Figure 7.18: Results transport hub scenario, with €50 transshipment costs per TEU

7.3.2. Difference between drought scenario without hubs and with hubs

All newly won regions are reached by transshipment to the road, and therefore, there's no difference in the scenarios of €90 and €50 pricing in Figure 7.19 and Figure 7.20. 2 NUTS regions past Kaub are now 1% cheaper for the €50 transport hub and waterway transport is still the preferred modality. For €50 transshipment at Kaub towards IWT for some areas, it starts to become profitable to use the transport hub. The competitive map is simulated if only IWT is possible from the different seaports and Rotterdam can transship at the transport hub. Shown in Figure 7.21 that with transport hub costs of €90 per TEU, it doesn't benefit the IWT network, and it will not be used. For the €50 transshipment in Figure 7.22, using a transport hub will benefit the transport and will save €3000 on transport from Rotterdam to areas passed Kaub. It turns out that the tariffs at the transport hub are now low enough for the location in Koblenz, but for the other hubs, the tariff is still too high to become beneficial to the network when it is used for water-to-water transshipment.

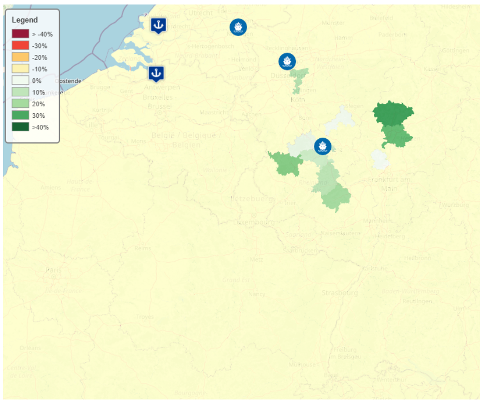


Figure 7.19: Transport cost improvement for drought scenario, with €90 transshipment costs per TEU at transport hub

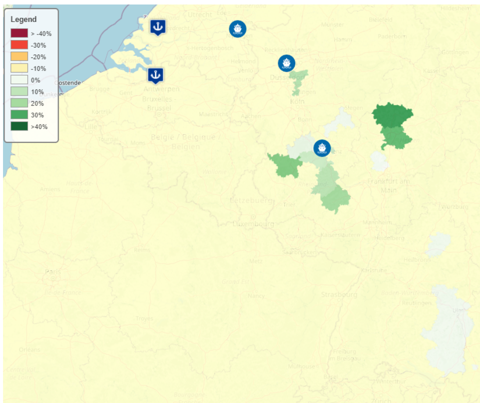


Figure 7.20: Transport cost improvement for drought scenario, with €50 transshipment costs per TEU at transport hub

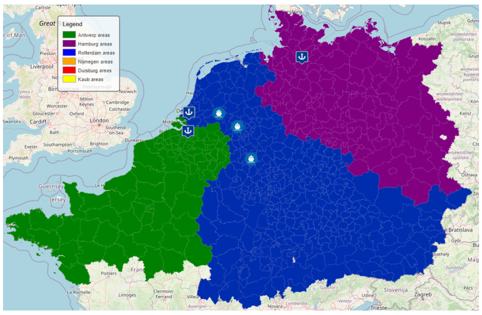


Figure 7.21: Only IWT transport possible with transshipment costs €90 per TEU

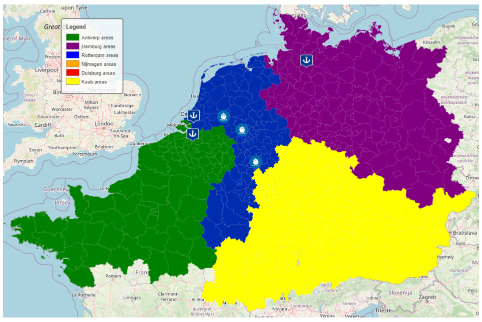


Figure 7.22: Only IWT transport possible with €50 transshipment cost per TEU

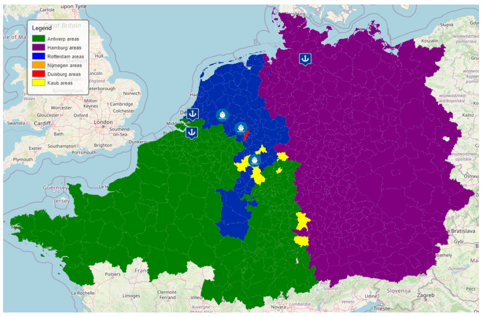


Figure 7.23: Results transport hub scenario, with €30 transshipment costs per TEU

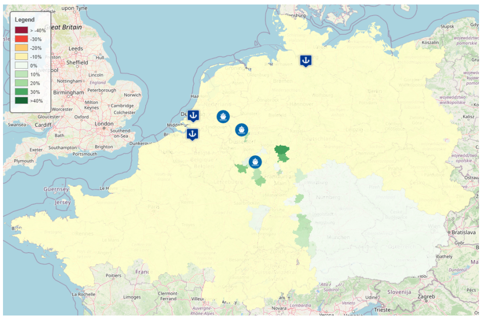


Figure 7.24: Transport cost improvement for drought scenario, with €30 transshipment costs per TEU at transport hub

The same simulation is done with €30 transshipment costs at the terminal towards rail and back-to-water transport onto another vessel. Figure 7.23 shows that more areas are now won by transport hub Kaub, but there is no difference for transport hubs Nijmegen and Duisburg. Figure 7.24 shows the difference compared to the drought scenario, and it shows that transshipping to rail starts to be beneficial from the transport hub at this price. The spread of the different modalities is again shown in Figure 7.25, where the transshipment possibilities are added to the waterway modality. Here, the cheapest solution is chosen, and looking at the intersection of the linear fit of the waterway costs and the railway costs, the transport hub alternatives improve the position of Rotterdam IWT compared to other modalities.

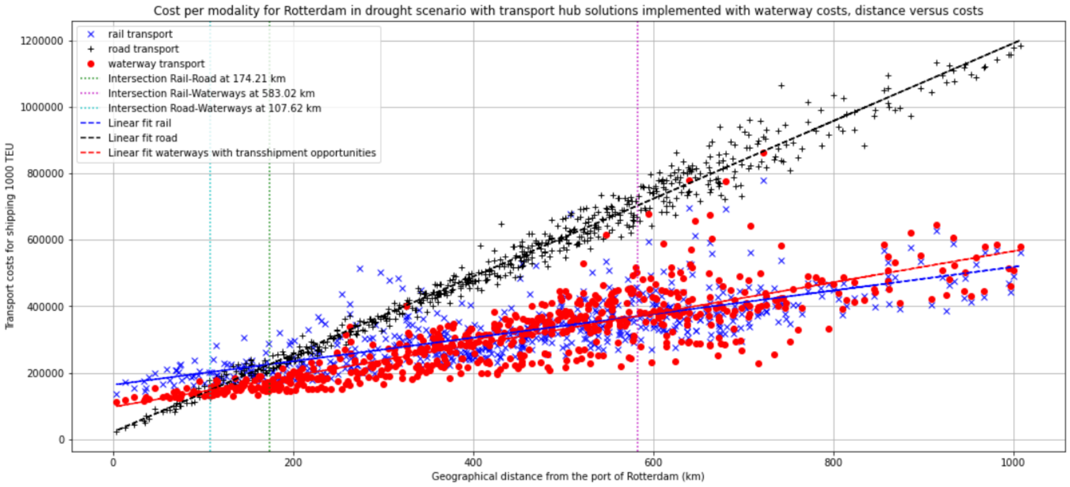


Figure 7.25: Modality spread port of Rotterdam, transport hub scenario

7.3.3. Transport hub at €50 per transshipment during baseline scenario

The transport costs of the transport hubs are modeled to determine the potential use of the hubs outside of the dry scenario. Being able to use the hub during the year will also help justify the investment costs of the hubs. Figure 7.26 shows the difference between the cheapest and second cheapest transport alternative. In Figure 7.27, the transport hubs are added to the waterway modality, and it shows that the competition between the waterway modality and railway modality is now closer in the hinterland.

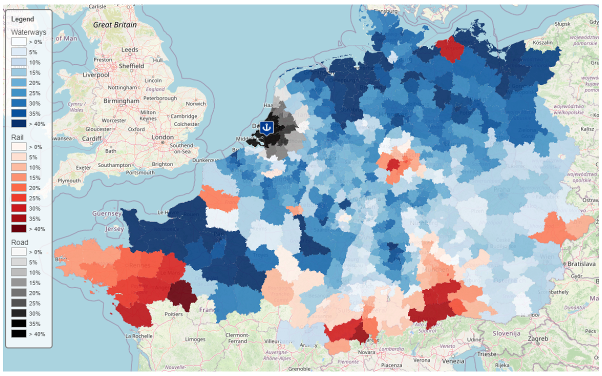


Figure 7.26: Cheapest modality alternative difference baseline port of Rotterdam

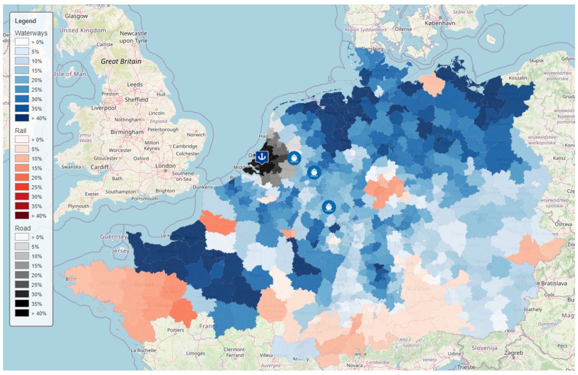


Figure 7.27: Cheapest modality alternative difference baseline port of Rotterdam, with transport hub solutions

The hubs provide a cheaper second solution after railway transport from the port of Rotterdam. To show the difference between transport from the hubs and 1 modality transport from the port of Rotterdam, without rail transport from Rotterdam, Figure 7.28 is created. It shows that for most hinterland areas, 1 modality of transport is a lot cheaper than using the hubs, but if rail transport is not possible, regions in the hinterland would be the cheapest to reach via the hub. Areas in Austria and Switzerland are now the cheapest to reach via the Duisburg and Kaub hubs. All these areas are won by transshipping from water to rail and would be efficient alternatives if there's not enough rail capacity towards these areas from Rotterdam. The areas will still be in competition with the other seaports, but there will be more alternative modalities to reach these areas.

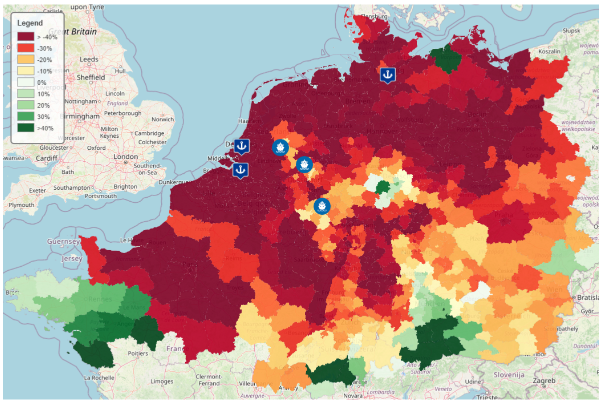


Figure 7.28: Competition between hub transport modes and IWT and road transport from Rotterdam

7.3.4. Effectiveness of transport hubs

The different costs for transshipment show the difference in the effectiveness of the hub, but how does the effectiveness correlate to the distance from the seaport, pricing for vessels, and difference in loading rate? For multiple hinterland regions, the transport price via water is shown in Table 7.1; here, the transport hubs only tranship from water to water. Here, it's visible that only the transport hub Kaub is cheaper than the transport without stops.

	AT314	AT315	DE711	distance from Rotterdam (km)
no hub	€ 579.858,46	€ 600.171,86	€ 299.009,71	
Nijmegen hub	€ 604.080,83	€ 624.394,23	€ 323.232,08	133,4
Nuisburg hub	€ 591.921,61	€ 612.235,01	€ 311.072,85	241
Kaub hub	€ 576.616,21	€ 596.929,62	€ 295.767,46	407,7

Table 7.1: Different transport prices for far hinterland transport in drought period

In Table 7.2, the savings for different regions are shown per transport hub when shipping from IWT back to IWT but with lower vessel capacities. It only saves €3,18 per TEU to tranship cargo at Nijmegen to regions between Nijmegen and Duisburg. This will never be possible knowing the cost values for transshipping containers from section 4.2. Providing that handling 1 TEU 1 time already costs €40, transshipping at Kaub seems to be the only location for cost-effective transshipment. In Table 7.2, the costs of transshipment are not factored in yet, and these costs must be lower than the prices in Table 7.2 for transshipment to be beneficial. Equation 7.1 is created to determine the savings of a transport hub in terms of distance from the seaport, capacity of the vessel before the hub and after the hub, and the cost of the vessel per km. If the costs of the transshipment are used, Equation 7.1 can be changed to Equation 7.2 to meet the situation where the transshipment is beneficial.

	area past Nijmegen	area past Duisburg	area past Kaub
Nijmegen hub	€ 3,18	€ 7,04	€ 23,71
Duisburg Hub		€ 6,98	€ 37,09
Kaub hub			€ 50,95

Table 7.2: Transport hubs savings per TEU for hinterland destinations in different areas

$$\text{Savings} = \text{d}_{\text{seaport}} \times \left(\frac{\text{vessel cost}_{\text{per km}}}{C_{\text{after}}} \right) \times \left(1 - \frac{C_{\text{after}}}{C_{\text{before}}} \right) \tag{7.1}$$

$$\text{d}_{\text{seaport}} \times \left(\frac{\text{vessel cost per km}}{C_{\text{after}}} \right) \times \left(1 - \frac{C_{\text{after}}}{C_{\text{before}}} \right) > \text{cost}_{\text{transshipment}} \tag{7.2}$$

7.4. Increase of Seaport competitiveness by adding Seaports

The model is also used to increase the number of seaports to test the validity of the model and if it still looks presentable when more than 3 ports are included. Two different groups of seaports are chosen, one variant where the same seaports are chosen as the research by de Leeuw van Weenen et al., 2019, and one variant where other seaports close to the port of Rotterdam are taken under consideration. A larger area is considered for these simulations due to the increased competition, and therefore larger NUTS regions are used, NUTS level 2. Different seaport groups are chosen, and therefore, the outline of the area is also slightly different; for the first scenario, more to the east, and for the second, a larger part of France is considered. Although the accuracy of the NUTS-regions is lower in Figure 7.29 and Figure 7.30 than the other model outputs, the areas of the Port of Rotterdam are well represented when in competition with the other seaports.

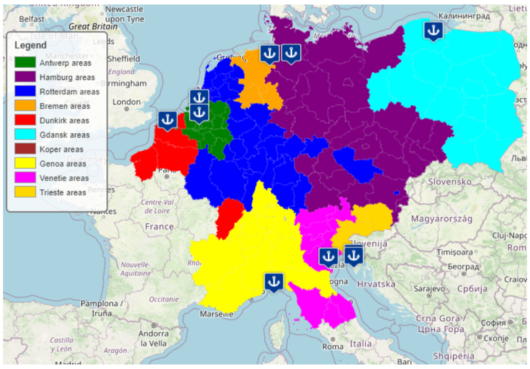


Figure 7.29: Competitive NUTS regions for 10 large seaports similar to the research of de Leeuw van Weenen et al., 2019

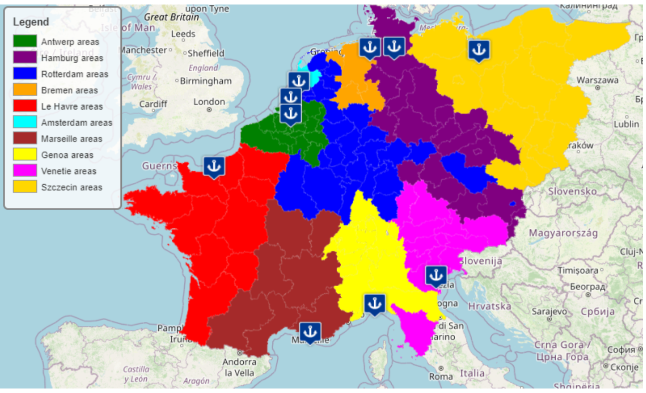


Figure 7.30: Competitive NUTS regions for 10 large seaports close to Rotterdam

7.5. Emissions for different modalities

The emissions are checked for the waterways from each seaport to see what the impact is of the transport hubs in the drought scenario, and the transport hub alternatives are checked to determine how much more sustainable they are compared to 1 modality transport from the port to hinterland regions. Only inland waterway transport is considered due to the lower emissions of railway transport, which will always win over IWT. Figure 7.31 show the IWT alternative with the lowest emissions, where Nijmegen and Kaub have the lowest emissions for the most hinterland regions. In Figure 7.32, the differences in using transport hubs for IWT are plotted with an energy use reduction between 5% and 25%. Areas using the transport hub in Nijmegen are reduced with 35 GJ and Kaub areas 280 GJ in energy use to transport 1000 TEU. This will respectively reduce the CO_2 emissions with 2500 kg and 20000 kg, 21 g and 164 g of N_2O, 172 g and 1378 g of CH_4, and 17 g and 131 g of SO_2.

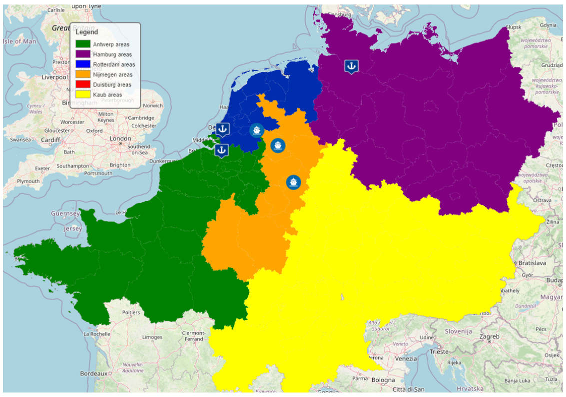


Figure 7.31: Competitive NUTS regions with lowest emissions on IWT transport

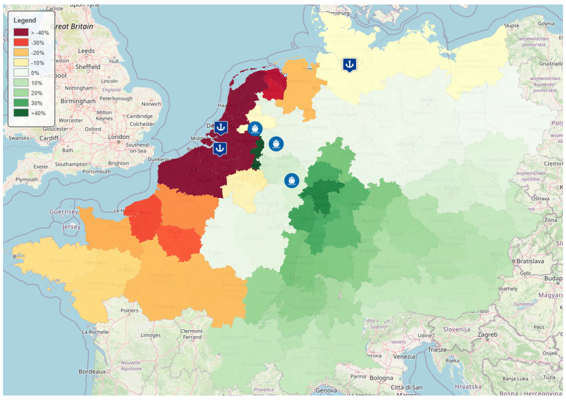


Figure 7.32: Difference in energy use when using the hub instead of direct IWT from Rotterdam

8

Discussion

This chapter discusses and analyzes the results provided in the previous chapters. Subsequently, the assumptions and limitations of the methods and the model are discussed, and necessary simplifications are explained to fit the research within the scope of the thesis.

8.1. Discussing the results of the transport model

The research results are divided into several parts, starting with the locations of the critical bottlenecks along the Rhine for low water levels. Next, the transport model is discussed, followed by the data analysis. The method for identifying suitable transport hub locations is then addressed, and lastly, the results from the transport competition model are discussed. First, a summary of the most important outcomes and results is given.

8.1.1. Summary of the results

The critical bottlenecks along the Rhine are found at Nijmegen, Duisburg, and Kaub, which posed the greatest navigable challenges, resulting in the largest delays and increase in transport costs. The transport model was created using existing transport networks from Demis, 2022, modality cost calculations derived from Meulen et al., 2023, and used level 3 NUTS regions as destinations. The baseline and drought scenarios were integrated by adding vessel capacities for hinterland regions, and the transport hubs were added to determine the cost-effectiveness of the hubs. Following the cargo analysis and a 54% transport reduction during the drought period, 43 % of the baseline cargo transport should be relocated to meet the CLARION objective of 80 % transport operability during climate-induced disruptions. The method used for finding suitable transport hub locations is the Best-Worst method, which uses the expertise of the professionals at the port of Rotterdam to find the ideal location for the transport hubs. Noordkanaalhaven in Nijmegen, Duisburg Gateway Terminal, and H & S Logistics in Andernach are chosen as locations for the transport hubs.

The transport competition model's results showed that the transport hub is effective when it comes to cost-saving alternatives. However, this depends on the transshipment cost at the terminal, which must be €50 or lower. It also depends on the hub's location, where the hub before bottleneck Kaub proved to be most effective. Transport hub Nijmegen is effective as a sustainable solution, and Duisburg is effective for transshipment towards rail.

8.1.2. Data analysis

The data analysis was conducted to find input values for the model for both scenarios and determine how much cargo would benefit from a transshipment at the transport hubs. Most of the reduced cargo transport stemmed from the inability of 6 barge-convoys to sail below water discharges of 1000m^3/s. These carry dry bulk, which has not been transshipped before, unlike containers. Although the same 54% reduction in container transport during this period would benefit from cargo transshipment at the terminal, dry bulk transshipment and finding ways to sail with 6-barge convoys on parts of the river during dry periods would make a large difference. However, legislation prevents this due to the prohibition on sailing with 6 barge convoys.

The transport hubs can help to work towards 80% operability by implementing the hubs along with other measures like updated vessel fleets investigated by Vinke et al., 2022. Looking at the data provided in subsection 5.2.2, the cargo that can be transshipped at each terminal is determined. The M-classes are looked at, and the amount of freight to reach 80% operability is determined. The daily amount of tonnes for Nijmegen to be transshipped is 558 tonnes, where the vessel has a full capacity of 2882 tonnes and a loading capacity of 68 % following from Table 5.14. This adds up to a necessary design capacity of 14.700 TEU per year at the hub. For each, the necessary capacity is calculated and displayed in Table 8.1. The total capacity of the hubs needs to be 255.000 TEU, with the most urgency in areas behind Kaub. The model is used to determine the best location for the hubs at this location.

	weight / day	**necessary M8 vessels / day**	**Yearly capacity hub**
Nijmegen hub	558 tonnes	0,28	14.700 TEU
Duisburg Hub	1705 tonnes	1,03	44.933 TEU
Kaub hub	7357 tonnes	5,26	193.725 TEU

Table 8.1: Total necessary yearly capacity of the hub at different locations depending on the reduced freight transport behind the hub

Here, only the container import from the port of Rotterdam is taken into consideration. Export from the hinterland areas, for which cargo can be bundled at the hubs towards Rotterdam, could also be considered. This can potentially double the capacity needed at the hubs, but due to other factors like vessel availability and port competition, the necessary capacity for the hubs is kept at 255.000 TEU.

The M8 vessel is chosen as the design vessel, and the maximum capacity and loading depth are taken for this vessel for container transport in the model. The loading rates for the vessels during the baseline and drought scenarios are, therefore, large. In reality, a vessel would sail with a smaller loading depth on most occasions because there are more empty containers on board, and 100% loaded is never reached due to delays and logistic problems to fill a vessel completely. The effectiveness of the hubs, however, depends on the difference in loading capacities before and after the bottleneck. The hubs will probably start taking effect at lower water levels than the water levels used in the baseline scenario. Still, for critical water levels, the effectiveness of hubs would be the same, which is also seen by the low water surcharges handled by the container companies. These significantly increase for the same water levels used as the drought scenario.

8.1.3. Transport hub location analysis

Before choosing the transport hub locations, the navigable bottlenecks are identified in the state of the art. Though several potential bottlenecks exist along the Rhine, three were selected to avoid excessive competition among hubs. The sizes of the hubs are optional, depending on the cargo that needs to be transshipped.

- **Nijmegen** was the major bottleneck in the Netherlands because this was the critical point when sailing from Rotterdam to Duisburg and is preferred above Arnhem and Tiel.
- **Duisburg** has the largest industry when it comes to freight transport in the Rhine Ruhr area and is therefore chosen before Wesel, Düsseldorf, and Köln.
- **Andernach**, just before Koblenz, turned out to be the ideal location for the hub before bottleneck Kaub. Although the bottleneck is a little further away, the area at Andernach and Koblenz has a slightly higher water level which is beneficial to the loading rate at the transport hub.

A thorough research into the German terminal situation could provide slightly different outcomes, but these weren't included in the search methods. The highest-graded location was in Duisburg, but the actual possibility of a hub for each location when it comes to future planning for the area isn't known. In reality, certain locations may not be available for freight transshipment during periods of drought. The Multi-Criteria Decision Making method can be reused for other purposes. Only a new workshop with experts in the field should be created to validate each criterion's grading criteria and weights.

The water level gradually decreases upstream, so an extra hub past the bottleneck back to a larger vessel isn't considered, but this could be effective past Kaub. Going further upstream past Kaub, the water level starts to increase again, and a potential hub at Mainz could be interesting. Here, cargo can be bundled further upstream, and the hub is used in reverse to increase the vessel's capacity.

8.1.4. Transport competition model results

The model shows reliable results when comparing the baseline scenario for 3 ports in section 7.1 and for more seaports in section 7.4 to the results from the port of Rotterdam shown in Figure 4.8. This shows that with standard cost functions for all seaports and an unmodified transport network, useful and reliable results can be retrieved. When looking at the Rotterdam-Rhine corridor, the transport model shows the most effective location for the hub to be at Kaub and then Duisburg. Based on emissions and increased capacity, Nijmegen can also be used, but to make the hub cost-effective, the transshipment costs need to be very low. The money saved for transshipment at a hub to a certain hinterland location is put in Table 7.2 to showcase the inefficiency at Nijmegen compared to the other hubs. Suppose transshipment is necessary towards rail and back to water. The costs to handle the cargo should be lower than these values, and this is probably only achievable for the transport hub in Andernach before Kaub. For transshipment to the road, the last-mile transport is increased, which is more easily earned back.

The transport hubs have shown to be beneficial during drought periods and are also interesting for transshipping cargo from water to rail in the baseline scenario. However, there is a very close difference between the costs and the savings, which makes large investments in such a hub risky, especially when the next drought period could be years away. The model proved to be beneficial in finding answers to the research questions and would be interesting to implement in solving other inland waterway problems.

8.1.5. Implications for the methods and the results

The methods used in the data analysis and the transport location analysis proved to be useful and reliable when implemented into the model. They facilitated effective values for cargo reduction and suitable locations for future transport hubs, but more research into the capacity of the hubs would be necessary before implementing them. The same methodology can be used, however, for similar research into finding terminal locations. Creating drought scenarios and developing loading capacities can be done in the same manner as shown in the report for other scenarios or different waterways, where both methods proved useful for a wider range of IWT problems. The transport competition model has been shown to be useful and reliable for simulating a wide range of scenarios. Potential implementations of extra seaports and emissions have been shown in section 7.4 and section 7.5, which showcase the model's potential and usefulness in simulating other IWT scenarios in Europe.

When looking at the results from the transport model and the cargo analysis, an effective method for implementing the hubs is found. The hub at Nijmegen is identified as the least effective for container cargo and is deemed the least necessary. In contrast, the hub before Kaub emerges as the most effective option. However, it is limited in size and can only be designed as a medium hub. The Duisburg Gateway Terminal proves to be the best location according to the BWM and can provide sufficient capacity. Pairing it with a transport hub at Andernach allows for the design of both terminals as medium-sized facilities, each with an annual capacity of 130,000 TEU. This setup will adequately handle the disrupted container cargo and improve operational efficiency to 80% for container transport from the Port of Rotterdam to the German hinterland. Referring to the BCTN terminals, an area between 30.000 and 40.000m^2 will be necessary, depending on whether one or two cranes are utilized. The rail access at Duisburg can be used for transshipment to rail, and Andernach can be used to reduce IWT costs. It is important to consider the value of enhancing the network's reliability against drought periods, as the cost-effectiveness of these hubs may not be sufficient to recoup the required investment costs.

8.2. Limitations and uncertainties

This section discusses the limitations and uncertainties of the analysis and model, aiming to clarify the simplifications made and their impact on the outcomes. These limitations are inherent to the research's scope and help concretize the research problem.

8.2.1. Model assumptions

The main model assumptions are explained in subsection 4.1.4, and some extra assumptions are explained with regard to interpreting the results.

- There are no border costs, and each port has the same costs for the same country. There is no home-country advantage.
- Emissions are not yet included in the costs of the transport model but could make the transport hub more interesting when there are heavier carbon taxes.
- The transport hubs are only in competition for areas with the port of Antwerpen and the port of Hamburg, where these ports are not making use of the hubs.
- Intermodal transitions are simplified in the model and don't capture the logistical difficulties of transshipping cargo from and to each modality. This is very much simplified in this model and will need more research to create more accurate values for transshipment.

While these simplifications are essential for the model's workability, they also impose limitations in predicting more local or nuanced competitive dynamics. For this purpose, complex systems within the port are simplified to standard values.

8.2.2. Limitations

The limitations of the model are mostly regarded as the assumptions made to create the model. The limitations are listed per aspect of the modal.

- **Limited number of seaports**: Although the largest seaports of North-Western Europe are used in the model, other ports could be influential in competition. The baseline scenario of the model is checked, however, for accuracy on the port competition with more seaports, and the outputs are given in section 7.4.
- **Uniform port calculations**: The advantages of ports in terms of infrastructure are not taken into account, and the waiting times and terminal costs are the same for seaports and inland ports.
- **Uniform vessel**: One vessel type is used now, while it could be beneficial to use large vessels before a transport hub and low-water vessels after the transport hub.
- **Uniform truck and train**: Just like the vessel, only one type of truck and train is used, which could differ significantly in reality.
- **Only container cargo**: Only container cargo is modeled in this report. This is because the transshipment of liquid and dry bulk isn't done from the port of Rotterdam. The vessel capacity and loading depth of the model could be used for dry bulk, but the logistics of transshipment aren't investigated in this report.
- **Unlimited number of vessels**: agent-based simulations are not used, and no limit is assumed on the used number of vessels. In reality, a set fleet composition must be used, which will transport the cargo as agents towards the hinterland.
- **Only 4 water levels used depended on the Rhine**: There are only 4 general water level areas created in the model. These are based on the distinctive bottlenecks, and other waterways are matched with these water levels. For a more accurate model, all water levels of European waterways should be entered manually.
- **Transport delays not considered for transport costs**: Potential queuing at the terminals could create delays which will, in terms, add costs to the transport. It will also depict the transport network more accurately because now, the waiting time at the terminals is assumed to be as short and efficient as possible.
- **Intermodal transitions**: the efficiency and challenges of switching between transport modes are not fully captured. Delays and inefficiencies in these transitions can influence the overall transport time and cost but are not explicitly modeled.

8.2.3. Uncertainties

Different aspects of the model were simplified to fit in the scope of this research and didn't require extensive modeling. The reason why is explained below:

- **Transshipment costs at the terminal**: the pricing for terminals isn't openly available, but an average value is provided by experts at the port of Rotterdam for terminal costs, which are also used for the cost at the transshipment terminal.
- **Costs per vessel type**: the costs for the Large Rhine vessel are determined by Panteia, but there is no such data for all vessels. To give more certainties of the influence of vessel fleet composition, this needs to be determined.
- **Dynamic water levels**: these are constantly changing, and there are uncertainties to the actual water level along the Rhine. The model simplified this and took the average of the baseline and drought period on 4 parts of the Rhine.
- **Future zoning plan for hub locations**: the availability of the locations isn't known, which may or may not make the transport hub possible.
- **Political and social factors**: a cooperative European transport network is considered with the integral need for efficiency. This could change, however, when governments move away from a united European Union and start implementing legislation and policies that prevent an integral transport hub from working.

9

Conclusion and Recommendations

The objective of this research is to create a method to quantify the impact of transport hubs on port-hinterland connections during periods of drought. By doing so, it aims to provide a practical solution that can be implemented to maintain efficiency and reliability in the face of climate-induced challenges. This report is focused on the Rotterdam-Rhine hinterland connection and will provide answers for this network, while the method can also be implemented on other waterways. The objective of this research is formulated in the main research question, which will be concluded in this chapter:

How can transport hubs be evaluated as cost-effective solutions along the Rhine corridor to make the Port-hinterland connection more resilient against climate change?

9.1. Conclusions

To achieve the objective of the research and answer the main research question, 5 sub-questions are posed. These sub-questions are answered below to provide an answer to the main research question. The first research question was based on investigating the literature on drought periods in North-Western Europe:

Which locations form critical bottlenecks for inland shipping on the Rhine, and what are the average delays and added transport costs due to the increase of necessary vessels?

The research identified three critical bottlenecks along the Rhine: Nijmegen, Duisburg, and Kaub, which were selected based on their navigational importance and the challenges posed during periods of low water discharge. Nijmegen was identified as the primary bottleneck in the Netherlands, as it represents the critical point for water depth due to the hard layer of the river bed for vessels sailing from Rotterdam to Duisburg. Duisburg, located in the Rhine-Ruhr industrial area, stands out due to its central role in freight transport within the region and its location downstream of a region of the Rhine where the water level decreases. Finally, Kaub, situated further upstream, is the most significant bottleneck due to its shallow navigable channel, severely limiting vessel capacities during low water periods. The extra costs are expressed in low water surcharges at the bottlenecks, which can increase the transport price per TEU up to 250%. When a certain critical water depth is reached, the transport obligation even ceases to apply. Carriers sell their services via the spot market, which makes transport for certain people too expensive. These low water periods lasted 80 days in 2018 and 37 days in 2022, causing massive delays in transport time. Knowing the critical bottlenecks on the Rhine, the transport competition model is considered to answer the second research question:

How can we model port-hinterland transport competition for different seaports and modalities, and how can transport hubs be implemented into this model?

Using existing models for port hinterland competition as a base and integrating transport hubs and water levels, the transport competition model was developed. The transport model was created using existing transport networks from Demis, 2022, modality cost calculations derived from Meulen et al., 2023, and used level 3 NUTS regions as destinations. The baseline and drought scenarios were integrated by adding vessel capacities for hinterland regions, and the transport hubs were added as nodes in the network to determine the cost-effectiveness of the hubs. The model shows reliable results when comparing the baseline scenario for 3 ports in section 7.1 and for more seaports in section 7.4 to the results from the port of Rotterdam shown in Figure 4.8. This shows that with standard cost functions for all seaports and an unmodified transport network, useful and reliable results can be retrieved. The integration of emissions also showed possible in section 4.6 by integrating them next to the cost function. Overall, the created model is useful for a wider range of IWT problems applicable in different regions in Europe. Different drought scenarios can be integrated to simulate in the desired regions, provided the water levels and transport inputs for these scenarios are investigated beforehand, as is done in this report to answer the third research question:

How much cargo must be relocated on another modality at the hub locations to guarantee the reliability of the hinterland shipping network for a critical low water level?

The objective of 80% operability during climate change disruptions is chosen as a measure for a reliable shipping network. To maintain this operability of the port-hinterland connection at 80% during periods of drought, approximately 43% of the baseline cargo transport needs to be relocated to alternative modalities at the designated transport hubs. Transport towards the German and Swiss hinterland was found to be reduced by 54% for all transport cargo.

Since transshipment for dry bulk and liquid bulk hasn't been done before, the hubs and the model focus on container cargo. The 22 largest ports in Germany and Switzerland are examined to find the specific container freight reduction during the drought period for locations passed each bottleneck. Cargo reduction between Nijmegen and Duisburg is assigned to the transport hub Nijmegen, between Duisburg and Kaub to Duisburg, and passed Kaub to the transport hub located before Kaub. The modeling results indicated that Nijmegen would need to transship 558 tonnes of container cargo daily, Duisburg 1705 tonnes, and Kaub 7357 tonnes. These values reflect the significant cargo volumes that need to be handled by transshipping to rail, road, or back to water with a lower vessel capacity to guarantee the reliability of the network. To handle all this cargo, an annual capacity for the hubs of 255.000 TEU is necessary and will be located at one hub or divided over multiple hubs depending on the outcomes of the transport model and the locations of the fourth research question:

How to identify suitable locations along the Rhine for transport hubs, considering existing infrastructure and accessibility to other transport modalities?

The Best-Worst Method was identified as the most suitable method for this research, and it was evaluated against other MCDM methods. This method utilized the expertise of professionals from the Port of Rotterdam to choose and weigh the importance of various criteria, including accessibility to other transport modalities, proximity to existing infrastructure, the feasibility of the locations in terms of cargo handling, the necessary investment and the influence of a potential transfer hub on residents and nature. Using the Best-Worst Method, optimal locations for transport hubs were determined at the Noordkanaalhaven in Nijmegen, Duisburg Gateway Terminal, and H & S Logistics in Andernach, just before Koblenz. These hubs were graded the highest based on their characteristics and potential to support cargo transshipment and maintain transport operability during drought-induced disruptions. For all 3 locations, different scales for the transport hub are possible, and therefore, the effect of the transport hubs is considered in the transport model to find an answer to the last research question:

How will these modality changes at the transport hubs affect the total transport costs of the cargo compared to 1 modality transport for the same destination?

First, the model was run based on the baseline scenario. It is checked for 14 different European ports to showcase the usefulness for a wider range of IWT problems in other regions in Europe, but only North-Western Europe's largest and most active ports are used for the transport hub scenario. After finishing the base case, the model implemented the drought scenario to simulate the transport cost changes in the network. For the third scenario, the 3 transport hubs were implemented to show the overall influence of the hubs on the drought scenario. In Figure 9.1, the increase of transport price of the cheapest mode of transport towards a hinterland destination is shown, where the price increase is shown in gradations of red, and it increases up to 50%. The influence of transport hubs on this drought scenario is shown in Figure 9.2, where the transshipment costs at the terminal are €50 per TEU, and the decrease in price is shown in gradations of green. Transport hub Andernach, before bottleneck Kaub, shows a reduction in the prices of reaching the destination for 18 regions and Duisburg for 2 regions. 9 regions benefit from transshipment back to water and 11 regions towards road.

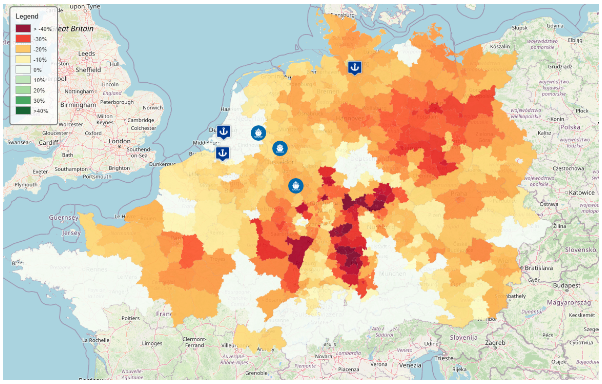


Figure 9.1: Percentage of increase in transport price from the port of Rotterdam during the drought scenario

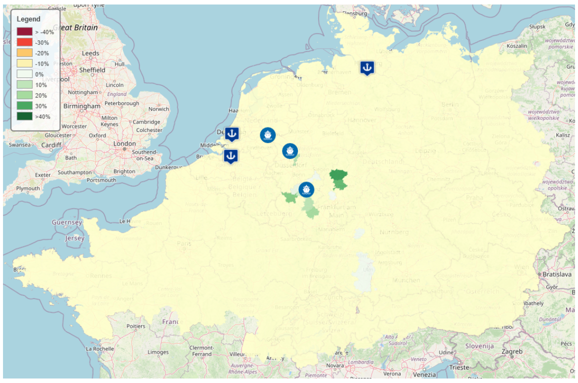


Figure 9.2: Influence of transport hubs on cheapest transport alternative from the port of Rotterdam

In these figures, railway transport came out as the cheapest modality for further hinterland transport, but in reality, this modality isn't capable of handling all the excess IWT cargo during the drought period. Therefore, the hubs' performance is checked if only IWT is possible and transshipment back to water is the only transfer. In Figure 9.3, the cheapest solution for transport towards a hinterland region is shown from each seaport or used hub. It shows in yellow that transporting via the transport hub before Kaub is now the cheapest solution for large parts in the hinterland. The effectiveness of the transport hubs during the baseline scenario is also checked, where it shows to be effective for transshipment towards rail for certain hinterland regions. Figure 9.4 shows this effectiveness for rail transshipment compared to IWT from the port of Rotterdam. Most regions are colored red, for which the transport hubs have no use, but the green area benefits from a transshipment towards rail from Duisburg or Kaub.

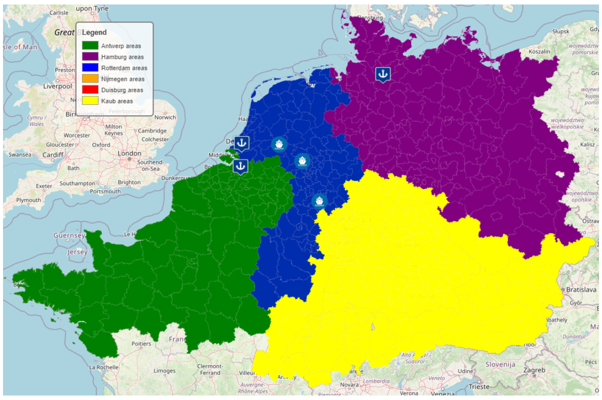


Figure 9.3: Only IWT transport possible with €50 transshipment cost per TEU

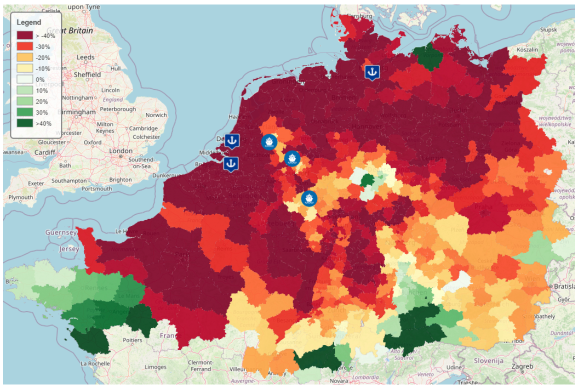


Figure 9.4: Competition between hub transport alternatives and IWT and road transport from Rotterdam

In Table 7.2, the savings for different regions are shown per transport hub when shipping from IWT back to IWT but with lower vessel capacities. The area past the transport hub determines the difference in loading rate before and after the hub. It only saves €3,18 per TEU to transship cargo at Nijmegen to regions between Nijmegen and Duisburg. Here, the costs of transshipment are not factored in yet, and these costs must be lower than the prices in Table 9.1 for transshipment to be beneficial. Equation 9.1 must be correct to make the transport hub cost-effective compared to transport without a hub. This Equation is in terms of distance from the seaport, capacity of the vessel before the hub and after the hub, and the cost of the vessel per km. If these savings exceed the costs, water-to-water transshipment is beneficial.

$$d_{\text{seaport}} \times \left(\frac{\text{vessel cost per km}}{C_{\text{after}}} \right) \times \left(1 - \frac{C_{\text{after}}}{C_{\text{before}}} \right) > \text{cost}_{\text{transshipment}} \tag{9.1}$$

	area past Nijmegen	area past Duisburg	area past Kaub
Nijmegen hub	€ 3,18	€ 7,04	€ 23,71
Duisburg Hub		€ 6,98	€ 37,09
Kaub hub			€ 50,95

Table 9.1: Transport hubs savings per TEU for hinterland destinations in different areas

The sustainable improvement of the transport hubs is also investigated with respect to energy use during IWT transport. Areas using the transport hub in Nijmegen have an energy reduction of 35 GJ for the IWT transport, and the Kaub area's energy consumption for IWT transport is reduced by 280 GJ for shipping 1000 TEU. This will respectively reduce the CO_2 emissions with 2500 kg and 20000 kg, 21 g and 164 g of N_2O, 172 g and 1378 g of CH_4, and 17 g and 131 g of SO_2.

In conclusion, transport hubs can enhance port-hinterland connections and make the network more resilient. However, their cost-effectiveness depends on considering transshipment costs, strategic placement, and integration with other transport modalities. The transport competition model proved to be useful for simulating the effect of the transport hubs on the Rotterdam-Rhine port-hinterland connection and showed to be applicable for implementation in other regions and scenarios as well. The method of analyzing the transport and water discharge data gave useful simplified inputs for the model, which can be easily reproduced for other scenarios and locations. The location analysis can be used as a step-by-step guide for other cases to find suitable terminal locations, but it needs to be extended and improved to be used in real life. Using these methods, the model can give visual representations of the transport competition, showcasing the problem of increasing low water levels and the need for a more resilient IWT network.

9.2. Recommendations

Improvements to the model are recommended to extend its applicability to different scenarios and areas of inland waterways. These enhancements could improve the accuracy of the results and broaden the model's implications for addressing various water-level challenges in inland waterway transport. These recommendations can be explored in further research or incorporated into future studies to refine and expand the model's capabilities.

Incorporate a vessel fleet into the model instead of one design vessel.
Further research into specific vessel costs for each vessel type can give different outcomes when alternating between used vessels. In this research, the same vessel was used before and after transshipment at the hub. Implementing a larger vessel before and a smaller vessel after the hub could give better outcomes. Low-water vessels can be implemented further upstream beyond the bottlenecks, increasing the hubs' effectiveness.

Include exports towards the port of Rotterdam.
While the current model focuses primarily on the impact of transport hubs on imports and cargo distribution from Rotterdam to hinterland regions, including export scenarios would provide a more comprehensive understanding of port-hinterland connectivity. This will increase the necessary capacity of the hubs and may differ in cargo type volumes from the import. By integrating these export flows, the model can better reflect the full spectrum of cargo movements, allowing for more effective planning, especially during periods of drought.

Include agent-based simulations with a certain number of vessels and vehicles.
To better simulate the network's capacity and assess real-world constraints, it is recommended to include agent-based simulations with a predefined number of vessels and vehicles. These simulations would help model the interaction between transport agents within the inland waterway network, accounting for capacity limitations. This approach would provide a more dynamic analysis, as it considers individual vessel and vehicle behavior, decision-making, and network performance under various conditions. Incorporating such simulations would allow the model to evaluate the efficiency of transport hubs and multi-modal connections more accurately. It would provide valuable insights into optimizing fleet utilization during disruptions.

Include dynamic water levels of the waterways.
The model simplified water levels by taking an average for baseline and drought periods across four sections of the Rhine. Adding water levels for other waterways and incorporating detailed water depth data into the IWT networks used in the model could improve the accuracy of vessel loading rates, enhancing the overall precision of the model.

Add the logistical advantages of seaports to terminal costs.
Seaports like the Port of Rotterdam provide logistical advantages significantly affecting terminal costs and overall transport efficiency. These advantages include economies of scale, advanced infrastructure, and streamlined customs procedures that lower the per-unit handling costs at terminals. Adding these advantages will provide better outcomes regarding the competitive positions of seaports over other ports. This can also be included for inland terminals and ports, where no difference is made between them. Large terminals and ports can significantly decrease prices when it comes to handling per unit.

Add more European seaports to the model.
Although the main competition in the North-Western European hinterland stems from the ports of Rotterdam, Hamburg, and Antwerp, the accuracy of the model would benefit from the inclusion of extra seaports. In section 7.4, this has already been tested, and it shows promising results implementing more seaports to the model.

Investigate transport hubs for dry bulk cargo.
Low water levels have a more significant impact on dry bulk cargo, yet the transshipment of this type of cargo has not been extensively explored. If the feasibility of dry bulk transshipment is investigated, it could be incorporated into the model, providing a more complete picture of cargo movement under such conditions.

The use of 6 barge-convoys for parts of the Rhine.
The legislation prohibits 6-barge convoys during critical water levels, but the data analysis shows the largest reduction of transported cargo with these vessels. If it's still possible to sail parts of the river with these vessels and transship cargo, it could prevent large freight reductions.

Investigate dropping barges at hubs and picking back up.
Shifting between 6-barge convoys and 4- and 2-barge convoys could be implemented by simply dropping the barge and picking it back up with another push boat. This could decrease the total distance traveled by the push boats.

Integrate a transport hub further upstream.
Consider integrating a transport hub at Mainz or at another inland port beyond the bottleneck Kaub to assess the efficiency of returning cargo to vessels for the final leg of the journey. The transport model and Equation 9.1 could help assess this case for effectiveness if research is done into the water level scenarios on this stretch of the Rhine.

Use only the transport hubs for dropping off excess cargo.
Instead of transshipping the entire throughput, hubs could be used to drop off excess cargo. This would reduce terminal fees and time, and fewer additional vessels or vehicles would be required to handle the excess cargo.

Further, Investigate the economic feasibility of the transport hubs While transport hubs may offer operational advantages during low water levels, the financial viability needs to be investigated in terms of the investment cost and yearly potential profit to determine if they would be worthwhile investments. The German authorities need to decide this.

Investigate socio-economic impacts of transport hubs on the hub locations It would be interesting to investigate the potential advantage for a region to facilitate the hub. Transport hubs have the potential to drive economic growth and job creation in the regions where they are located.

Add queuing and terminal waiting times to the model
The transport delays and congestion at the ports play a part in the increased expenses during the drought period. Integrating these factors into the model could show potential transport delays of the cargo and also show the increase in costs due to longer waiting periods for the vessel at the ports.

More research into transshipment of cargo between modalities
The assumption is made in this model that the cost for transshipping cargo is a fixed value similar to the terminal handling fees. This will differ, however, depending on the potential of the hub, the type of modalities used for transshipment, and the amount of cargo that is handled.

Add sensitivity analysis on transport cost calculations
General cost calculations are used in this research where the sensitivity of the difference cost factors can still be checked. These factors include the cost per kilometer per modality or the cost of terminal handling and terminal time. How would the network react when looking at the increase in the cost of fuel or looking at increased prices due to reduced terminal competition?

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A

Low water surcharges

A.1. Contargo

Level at Emmerich Rhine km 851,9	LWZ per 20′ full	LWZ per 40′ full
70 - 61 cm	€25,00	€50,00
60 - 51 cm	€30,00	€60,00
50 - 41 cm	€40,00	€75,00
40 - 31 cm	€50,00	€100,00
30 cm or below	By agreement	

Table A.1: Low water level surcharges at Emmerich (Contargo, 2024 Contargo, 2024), Applies to the Emmerich and Emmelsum-Voerde terminals.

Level at Ruhrort Rhine km 780,8	LWZ per 20′ full	LWZ per 40′ full
300 - 271 cm	€15,00	€25,00
270 - 251 cm	€30,00	€45,00
250 - 221 cm	€55,00	€80,00
220 - 201 cm	€80,00	€105,00
200 - 181 cm	€110,00	€135,00
180 cm or below	By agreement	

Table A.2: Low water level surcharges at Ruhrort - Duisburg (Contargo, 2024 Contargo, 2024), Applies to all terminals south-east of Wesel, up to and including Neuss.

Level at Cologne Rhine km 780,8	LWZ per 20′ full	LWZ per 40′ full
195 - 176 cm	€25,00	€40,00
175 - 146 cm	€45,00	€70,00
145 - 126 cm	€70,00	€95,00
125 - 106 cm	€100,00	€120,00
105 cm or below	By agreement	

Table A.3: Low water level surcharges at Cologne (Contargo, 2024 Contargo, 2024), Applies for all terminals from Koblenz to Cologne (Bonn/Koblenz).

Level at Kaub Rhine km 546,3	**LWZ per 20′ full**	**LWZ per 40′ full**
150 - 131 cm	€40,00	€50,00
130 - 111 cm	€55,00	€75,00
110 - 101 cm	€75,00	€90,00
100 - 91 cm	€90,00	€145,00
90 - 81 cm	€120,00	€165,00
80 cm or below	By agreement	

Table A.4: Low water level surcharges at Kaub (Contargo, 2024 Contargo, 2024), Applies for all terminals south of Koblenz.

A.2. Hutchison Ports

Level	**Between (m)**		**20 FT**	**40 FT**
1	3.00	2.71	€10,00	€20,00
2	2.70	2.51	€25,00	€35,00
3	2.50	2.21	€45,00	€65,00
4	2.20	2.01	€65,00	€85,00
5	2.00	1.81	€90,00	€110,00
6	1.80	1.71	€144,00	€184,00
7	1.70	1.61	€207,00	€266,00
8	1.60	1.51	€303,00	€393,00
9	1.50	1.41	€350,00	€450,00
	Under 1.41		Upon request	Upon request

Table A.5: Low water surcharge at Duisburg

A.3. Maersk

Measuring Point Pegel DUISBURG-RUHRORT*	**20′**	**40′**
< 271 cm	€20,00	€25,00
< 251 cm	€40,00	€52,00
< 226 cm	€60,00	€75,00
< 201 cm	€85,00	€100,00
< 181 cm	€125,00	€180,00
< 161 cm	€165,00	€260,00

Table A.6: Low water level surcharges at Ruhrort - Duisburg (Maersk, 2024 Maersk, 2024)

Measuring Point Pegel KAUB*	**20′**	**40′**
< 151 cm	€30,00	€40,00
< 131 cm	€45,00	€60,00
< 111 cm	€60,00	€75,00
< 101 cm	€75,00	€100,00
< 91 cm	€100,00	€135,00
< 81 cm	€175,00	€225,00
< 71 cm	€240,00	€300,00
< 61 cm	€320,00	€425,00
< 51 cm	€475,00	€625,00
< 41 cm	€600,00	€775,00
< 31 cm	€775,00	€950,00

Table A.7: Low water level surcharges at Kaub (Maersk, 2024 Maersk, 2024)

B

Transport model explanation

This appendix is written to provide a clear step-by-step explanation of how to use the transport model. This is written as a walk-through of the model, where each operation is explained specific decisions and inputs are defined, and where changes can be made. To make the explanation not too extensive, specific functions are shown in **??**.

The entire model can be accessed via: https://github.com/TUDelft-CITG/Network-Competitiveness
This research is entered under the branch: LVDP_thesis

B.1. model set up

First, the locations of the seaports and transport hubs are determined. This can be done in two different ways, the name of the location and the GPS coordinates. The NUTS level is defined for the accuracy, the name of the scenario, and the number of TEUs that need to be transported. Then the base-case map is created to show the start of the network. The first cell loads all the functions and definitions created for the model.

```
#standard notebook imports
import matplotlib.pyplot as plt
%matplotlib inline
from networkcompetitiveness import *
import pandas as pd
```

```
# Find port locations on the network by name
rotterdam_port = 'Botlek'        #central location in Port of Rotterdam
hamburg_port = 'Tollerort'       #central location in Port of Hamburg
antwerp_port = 'Lillo-Fort'      #central location in Port of Antwerpen
nijmegen_hub = (51.85821220359286, 5.829979283008339)
duisburg_hub = (51.45041952093527, 6.756001918324492)
kaub_hub = (50.441506263495135, 7.426886857872669)

nuts_level = 3      # 0-3 can be chosen, 0 is country size and 3 is smallest possible regions
scenario = 'basecase' # scenario name
TEU = 1000              # number of containers that are simulated to be transported
refresh = False         # True if new scenario is used, else False
```

```
    basecase(rotterdam_port, hamburg_port, antwerp_port)
```

The base map is shown in Figure B.1, tools on the left can be used to draw poly-lines, polygons, markers, rectangles, and circles. Drawn lines and polygons in the base map can be saved and used to add waterways and railways and create NUTS outlines and water depth areas to determine vessel capacities. The NUTS region used for this research is shown in Figure B.2 and the command run to create the outline is:

```
gp_df_calc, df_base_case, basecase_outline_gpd = nuts_clean(nuts_level=nuts_level,gdf_name='
    nuts_basecase')
nuts_regions_map(gp_df_calc)
```

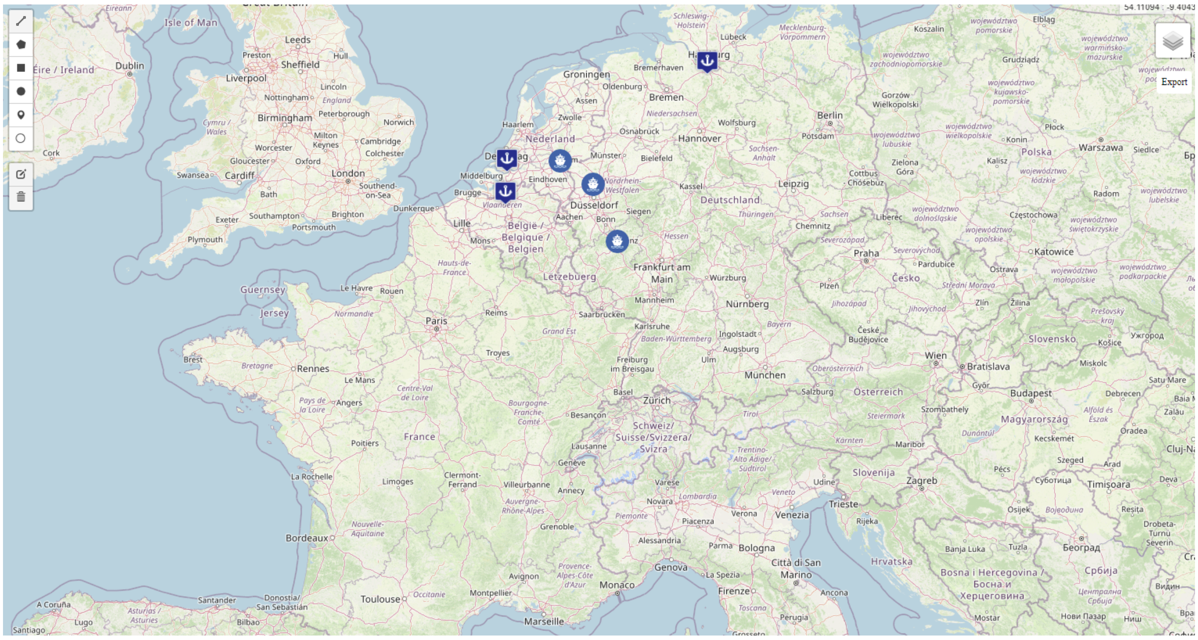


Figure B.1: Base map for the model

B.2. Transport networks

After this, the networks are imported, modified, and added to the model. Different networks were checked for better results but weren’t fully connected, and therefore the networks stayed the same as were already in the model. Which are the most updated of the data from **Demis2017ETISPLUSData**.

```
#importing the data
waterways_gpd, railways_gpd = import_network_data(case=’basecase’)

#waterway network changed to fit the base map
df_new_waterways = gpd.sjoin(waterways_gpd, basecase_outline_gpd, how=’inner’, op=’intersects’)
df_new_waterways.to_file(os.path.join(’data’,’waterways’,’ww_shape_bc.shp’))
ww_data = os.path.join(’data’,’waterways’,’ww_shape_bc.shp’)

#updated railway networks
df_new_railway = gpd.sjoin(railways_gpd, basecase_outline_gpd, how=’inner’, op=’intersects’)
df_new_railway.to_file(os.path.join(’data’,’railways’,’rail_shape_bc.shp’))
rail_data = os.path.join(’data’,’railways’,’rail_shape_bc.shp’)
```

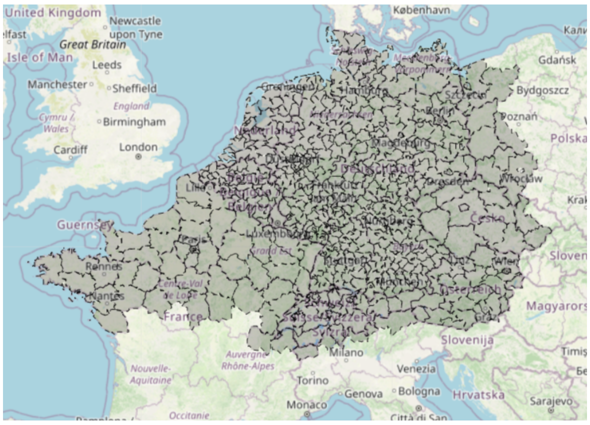


Figure B.2: Outline and NUTS regions used for the research

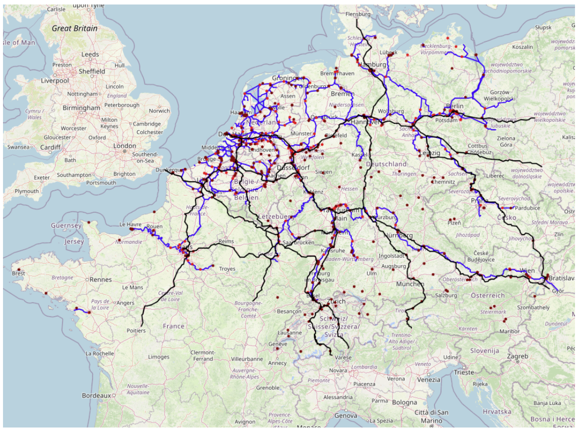


Figure B.3: Transport network, inland ports, and inland terminals for the specific outline

In the next command, the transport network files are worked out in the definition, names for railway networks and waterway networks are created, and nodes for seaports and hubs are created.

```
FG_IWT, FG_IWT_gpd, FG_rail, FG_rail_gpd, rotterdam_IWT_node, rotterdam_rail_node,
    hamburg_IWT_node, hamburg_rail_node, antwerp_IWT_node, antwerp_rail_node,
    nijmegen_IWT_node, nijmegen_rail_node, duisburg_IWT_node, duisburg_rail_node,
    kaub_IWT_node, kaub_rail_node = convert_modality_files(ww_data, df_new_waterways,
    rail_data,df_new_railway,rotterdam_port,hamburg_port,antwerp_port,nijmegen_hub,
    duisburg_hub,kaub_hub,case='basecase', strategy=scenario)
```

Next, the ports and terminals are added to the model. The ports and terminals are then assigned a water depth value as explained in subsection 4.1.3.

```
df_new_ports, reshaped_port_data, df_new_terminals, reshaped_terminal_data =
    reload_inlandports_terminals_to_network_bc(basecase_outline_gpd)
```

```
# add to waterway network
port_df = closest_node_to_port(FG_IWT, df_new_ports, rotterdam_IWT_node, False) # Create
    Dataframe
add_port_nodes_to_graph(FG_IWT,port_df,'port_node') # Add port node names to waterway graph
```

```
# add to railway network
terminal_df = closest_node_to_terminal(FG_rail, df_new_terminals, rotterdam_rail_node,
    refresh) # Create Dataframe
add_port_nodes_to_graph(FG_rail, terminal_df, 'rail_node') # Add terminal node names to
    railway graph
```

```
# Load the water depth GeoDataFrames outside of the function
waterdepth1_gdf = gpd.read_file(os.path.join('data', 'waterdepth1.geojson'))
waterdepth2_gdf = gpd.read_file(os.path.join('data', 'waterdepth2.geojson'))
waterdepth3_gdf = gpd.read_file(os.path.join('data', 'waterdepth3.geojson'))
waterdepth4_gdf = gpd.read_file(os.path.join('data', 'waterdepth4.geojson'))

# Combine the GeoDataFrames into a list
waterdepth_gdfs = [waterdepth1_gdf, waterdepth2_gdf, waterdepth3_gdf, waterdepth4_gdf]

# Apply the function to your ports DataFrame
port_df = add_water_depth_to_ports(port_df, waterdepth_gdfs)

# Print the updated port_df to check results
port_df

# Apply the function to your terminal DataFrame
terminal_df = add_water_depth_to_ports(terminal_df, waterdepth_gdfs)

# Print the updated terminal_df to check results
terminal_df
```

B.3. Calculations

The next step is to carry out the calculations for the cargo over the created transport network. An extensive definition is created to determine the distance and costs for each modality to transport the cargo to each hinterland destination.

```
# calculate and plot for the port of Rotterdam
df_rotterdam = calculate_distances_and_traveltimes(rotterdam_IWT_node, rotterdam_rail_node,
    FG_IWT, FG_rail,port_df,terminal_df, gp_df_calc[['NUTS_ID', 'points']], TEU=1000, scenari
    ='basecase',debug=False)
df_rotterdam.head()
```

```
# calculate and plot for the port of Hamburg
df_hamburg = calculate_distances_and_traveltimes(hamburg_IWT_node, hamburg_rail_node, FG_IWT,
     FG_rail,port_df,terminal_df, gp_df_calc[['NUTS_ID', 'points']], TEU=1000, scenari='
    basecase',debug=False)
df_hamburg.head()
```

```
# calculate and plot for the port of Hamburg
df_antwerp = calculate_distances_and_traveltimes(antwerp_IWT_node, antwerp_rail_node, FG_IWT,
     FG_rail, port_df,terminal_df, gp_df_calc[[’NUTS_ID’, ’points’]], TEU=1000, scenari=’
    basecase’, debug=False)
df_antwerp.head()
```

For each modality the shortest distance is found, using either the OpenStreetMap or a shortest path function over the transport network. Using the costs functions described in section 4.2 the costs for the total transport of 1000 TEU are calculated. Then the results are combined and sorted for the cheapest transport alternative for all 3 seaports. The results are saved and stored so that in other notebooks the results can be compared. The Dataframe df_results() is shown in Figure B.4.

```
# Calculate and combine the results in dataframes
gp_df_plot_rotterdam, gp_df_plot_hamburg, gp_df_plot_antwerp, gdf_mod_rdam, gdf_mod_hburg,
    gdf_mod_awerp, gdf_all, df_results = results_scenario(gp_df_calc,
  df_rotterdam, df_hamburg, df_antwerp, scenario=scenario, calibration=0)
df_results.head()
```

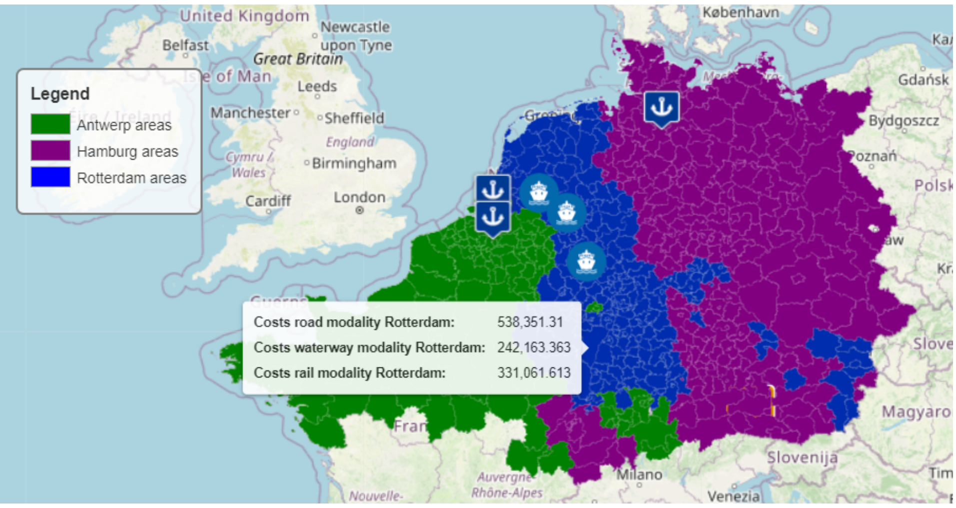
NUTS_ID	rotterdam_road	rotterdam_waterway	rotterdam_rail	hamburg_road	hamburg_waterway	hamburg_rail	antwerp_road	antwerp_waterway	antwerp_rail	geometry
AT314	970994.099333	374781.902909	432096.776220	914838.281333	422685.821359	378355.123998	933377.552333	384636.846565	388517.110427	POLYGON ((14.48276 48.10564, 14.46977 48.10003...
AT315	939540.755333	396964.126504	421799.290447	883384.937333	444868.044954	368057.638226	901924.208333	406819.070160	378219.624654	POLYGON ((13.75402 48.11806, 13.75765 48.11234...
DE600	493476.485333	171130.933932	255699.586056	18690.095333	104284.151560	131994.937814	548420.513333	176674.339739	265237.568535	MULTIPOLYGON (((9.94538 53.65293, 9.95059 53.6...
DE711	451253.090333	214982.892381	237368.540524	499959.701333	262886.810831	250108.043254	413636.543333	224837.836037	227813.109186	POLYGON ((8.72571 49.95421, 8.73453 49.94858, ...
DE712	435784.679333	194568.071949	269299.625524	474892.388333	242471.990399	282039.128254	398168.039333	204423.015605	259744.194186	POLYGON ((8.59024 50.15954, 8.58867 50.16843, ...

Figure B.4: Combined results of all transport calculations towards hinterland NUTS regions

B.4. Showing the results and port maps

The combined results are compared to find the cheapest seaport and mode of transport to reach a hinterland destination. The seaport that can carry out the cheapest ’wins’ the region. The areas won by the port of Rotterdam are shown in blue, the areas won by the port of Hamburg in purple, and the areas won by the port of Antwerp in green.

```
port_map(gp_df_plot_rotterdam, gp_df_plot_hamburg, gp_df_plot_antwerp, rotterdam_port,
    hamburg_port, antwerp_port,
            FG_IWT_gpd, df_new_ports, df_new_terminals, FG_rail_gpd, show=False)
```



Costs road modality Rotterdam: 538,351.31
Costs waterway modality Rotterdam: 242,163.363
Costs rail modality Rotterdam: 331,061.613

Figure B.5: Results of the hinterland competitive basecase model

In Figure B.5 it also shows that if you hold the computer mouse on a region, it shows the seaport that is the cheapest and for this seaport all the modality costs. Here the cheapest mode of transportation is IWT via the port of Rotterdam for €242.163,36. This seems like a correct cost estimation of €242 per TEU and comparing this to the barge rates in Figure 3.3 and Appendix A. Other maps are also possible to create in the model. Each port area can looked at individually to see the dominant modes of transport. In Figure B.6 Hamburg is taken as an example.

```
geo_data_2_plot = gp_df_calc[['FID', 'geometry']].reset_index(drop=True)
data_2_plot = gp_df_plot_rotterdam[['FID', 'costs_road']].reset_index(drop=True)

geojson_modality('Hamburg',df_results,geo_data_2_plot, rotterdam_port, hamburg_port,
    antwerp_port, FG_IWT_gpd, df_new_ports, df_new_terminals, FG_rail_gpd, show=False)
```

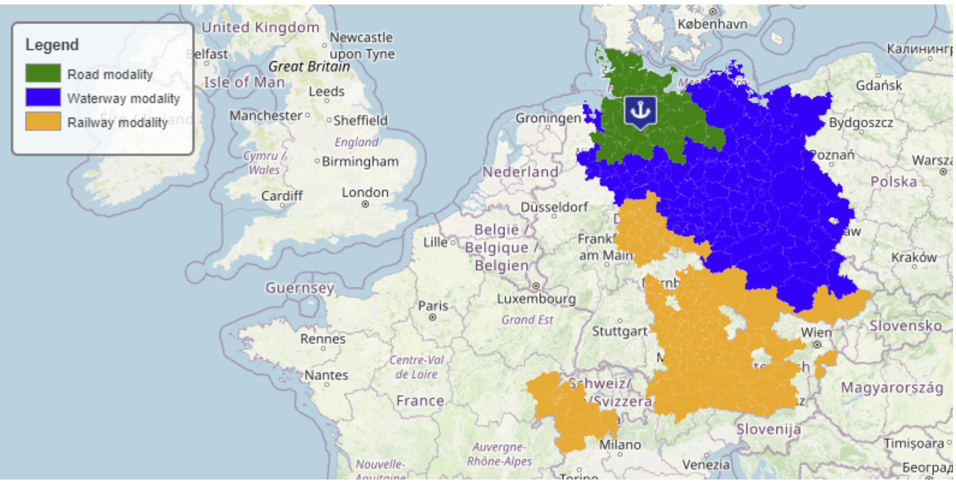


Figure B.6: Hamburg areas divided in cheapest modality

Other maps can also be created, and the use of some important functions is more precisely described in the model via the GitHub repository.

C

BWM Method

This format is created to get all the input on the criteria, Best-Worst Method, and grading methods of the experts working at the Port of Rotterdam. A workshop was hosted on 17-06-2024 to get all the inputs from the experts. The weights are calculated using the BWM solver via Excel from bestworstmethod.com bestworstmethod.com, 2024. The different weights assigned by the experts are entered in the tables below, where the conclusion of the Best criterion was the handling and the business case of the potential location. The Worst criterion or the least important criterion turned out to be road access due to the extensive road network available in Holland and Germany.

	Handling capacity	**Storage capacity**	**Quay Length**	**Investment costs**
Weights	0,24	0,163	0,109	0,163
	Environmental effects	**Local residents**	**Road access**	**Rail access**
Weights	0,065	0,065	0,031	0,163

Table C.1: Weights for Expert 1

	Handling capacity	**Storage capacity**	**Quay Length**	**Investment costs**
Weights	0,15	0,09	0,064	0,372
	Environmental effects	**Local residents**	**Road access**	**Rail access**
Weights	0,09	0,033	0,05	0,15

Table C.2: Weights for Expert 2

	Handling capacity	**Storage capacity**	**Quay Length**	**Investment costs**
Weights	0,244	0,098	0,074	0,244
	Environmental effects	**Local residents**	**Road access**	**Rail access**
Weights	0,098	0,074	0,021	0,147

Table C.3: Weights for Expert 3

Drought-resilient port-hinterland connections: Investigating the impact of modality transfer hubs

Main Research question:

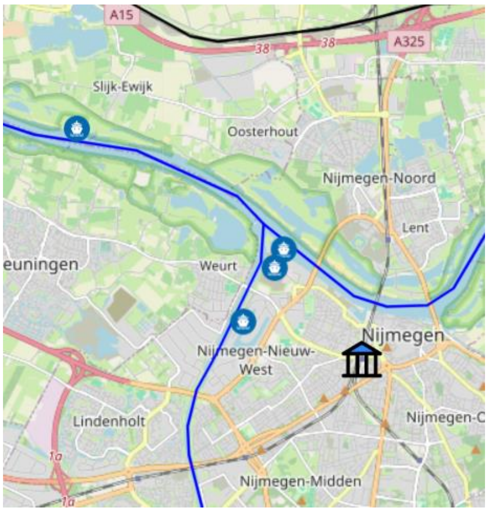
Can transport hubs be a cost-effective solution along the Rhine corridor to make the Port-hinterland connection more resilient against climate change?

With the sub-questions designed to help answer the main research question:

Which locations form critical bottlenecks for inland shipping on the Rhine and what are the average delays and added transport costs due to the increase of necessary vessels?

Nijmegen, Duisburg and Kaub identified as critical bottlenecks.

Which locations along the Rhine are suitable as transport hubs whit previous existing infrastructure and accessibility to other modalities?



Nijmegen not considered as a big bottleneck for container transport. Dry bulk travels from A to B and not yet make use of transport hubs. Handling 1 large inland vessel per day is 100 TEU and equal to 30.000 TEU yearly.

Potential locations for inland transport hubs

The potential locations for the transport hubs are found by using the main searching criteria:

- Minimum 280 m quay walls (to accommodate 2 inland vessels, 140 m)
- Connection to road or rail network
- Minimum surface area 10.000 m2 (capacity 30.000 TEU per year, BCTN 2024 [3])
- Existing infrastructure or adjacent to existing infrastructure
- Located before the navigable threshold that causes the bottleneck.

Additional: minimum area minimum 40.000 m2, else it only costs money

Additional: minimum space can also be for only 1 vessel

Best Worst Method

To determine the most efficient location for the inland transport hubs, the Best Worst Method is used to give weights to the different criteria's. The criteria's are derived from the literature and checked by experts in the field off inland transportation.

Determine the best (e.g. the most desirable, the most important) and the worst (e.g. the least desirable, the least important) criteria based on the opinion of the decision-maker. You can choose the Best and the Worst from the drop-box next to "Select the best", and "Select the worst" respectively.

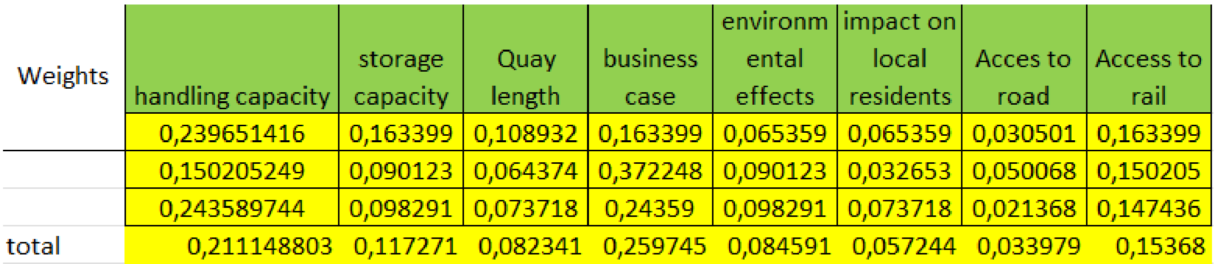
The meaning of the numbers 1-9:
1: **Equal** importance
2: Somewhat between Equal and Moderate
3: **Moderately** more important than
4: Somewhat between Moderate and Strong
5: **Strongly** more important than
6: Somewhat between Strong and Very strong
7: **Very strongly** important than
8: Somewhat between Very strong and Absolute
9: **Absulutly** more important than

Criteria	
Handling capacity	number of berths and cranes to handle cargo
Storage capacity	facilitate storage when the low water levels cause congestion
Quay length	number of vessels able to more
Investment costs	land purchase, construction and other investments
Environmental effects	Effects of inland terminal(-related) operations on the environment, e.g. release of hazardous materials or emissions in surroundings.
Impact on local residents	regional traffic congestion/competition and economic development
Access to road network	transport infrastructure and regional traffic competition
Access to rail network	rail infrastructure and traffic competition
Change investment costs to business case by adding operating costs	

1 outcome is shown below:

Best to Others	Handling capacity		Others to the Worst	Road access
Handling capacity	1		Handling capacity	9
Storage capacity	3		Storage capacity	7
Quay length	4		Quay length	5
Business case	1		Business case	9
Environmental effects	3		Environmental effects	7
Impact on local residents	4		Impact on local residents	5
Access to road network	9		Access to road network	1
Access to rail network	2		Access to rail network	8

Handling and business case Best criterion, road access Worst criterion, outcome of the weights of each criteria for each expert and the total average value shown:



Weights	handling capacity	storage capacity	Quay length	business case	environmental effects	impact on local residents	Acces to road	Access to rail
	0,239651416	0,163399	0,108932	0,163399	0,065359	0,065359	0,030501	0,163399
	0,150205249	0,090123	0,064374	0,372248	0,090123	0,032653	0,050068	0,150205
	0,243589744	0,098291	0,073718	0,24359	0,098291	0,073718	0,021368	0,147436
total	0,211148803	0,117271	0,082341	0,259745	0,084591	0,057244	0,033979	0,15368

Grading Criteria

For each criterion boundaries are determined to give a grade. The grades for each criterion are scored from 1 (bad) to 5 (good) determined separately following the following guide:

Criteria	Grade
Handling capacity	Operating berth: 1,2,3 grade: 1,3,5 Addition: …
Storage capacity	Surface area terminal: 10.000-25.000-40.000-65.000-100.000 Grade: 1,2,3,4,5 (Based on BCTN terminals) Addition: …
Quay length	Vessels able to moore: 2,3,4,5,6 grade: 1,2,3,4,5 *Design vessel size? Maximum or average?* Addition: …
Investment costs	For each investment that is required, the grade decreases by a number (see below). The necessary investments are: foundation, quay wall, old owner must be bought out, terminal infrastructure. Addition: …
Environmental effects	2 points are deducted for each aspect that applies to the location: Close to protected environment & green field location. Addition: …
Impact on local residents	For each impact on the residents, the grade decreases by 1. leaving home, noise pollution, traffic congestion, horizon pollution. Addition: …
Access to road network	Easy connection to highway, district road, village road Grade: 5,3,1 *What could be used as radius for distance to type of road?* Addition: …
Access to rail network	Not available, available but full capacity, available Grade: 1,3,5 Addition: …
Business case	Add factor for operating costs: Large terminal gets extra point
Local residents	Local terminal restrictions by authorities: -1 or -2

To determine the investment required per location, the existing infrastructure at the location is examined. 4 investments are taken separately here and for each investment required, a number will be deducted from the grade per investment. The quay wall investment is to lay a quay length for 2 vessels to more, the foundation investment is per 10.000 m2, buying out the owner present at the terminal can cause a lot of trouble and will cost 1 number in the grade and the investment for the operating crane is determined to increase handling capacity. In this way if a location is picked where the owner needs to be bought out, foundation for 40.000 m2 is planned along with room for 4 vessels and 2 operating berths, the grade will be 1. Because lower than 1 isn't possible, this is the maximum investment that can be done per terminal.

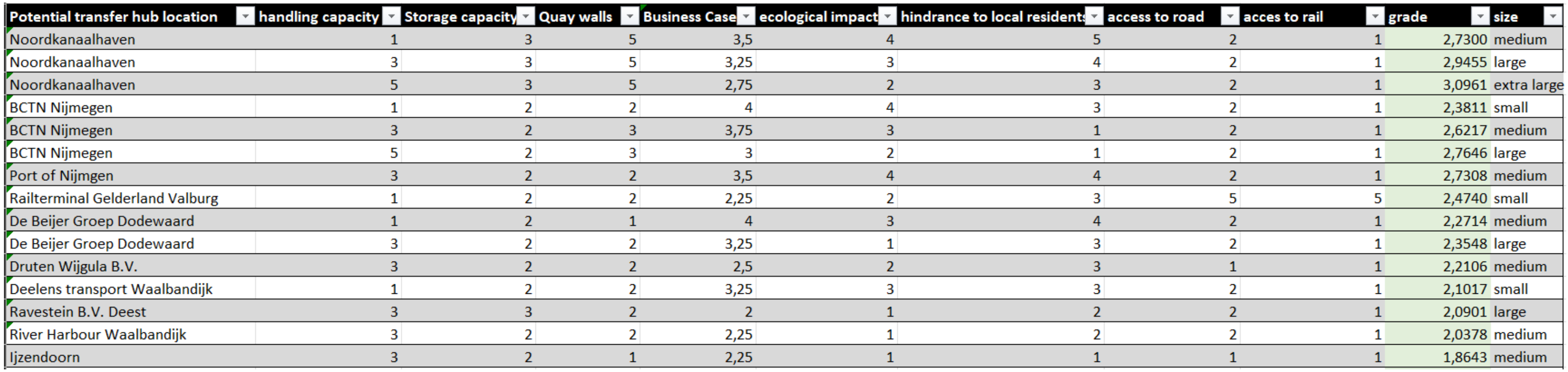
investment	quay wall	foundation	buy out owner	operating crane	Size small or large
grade	-0.5	-0.25	-1	-0.5	-1 ^ +1

.

D

Complete grading of potential transport hub locations

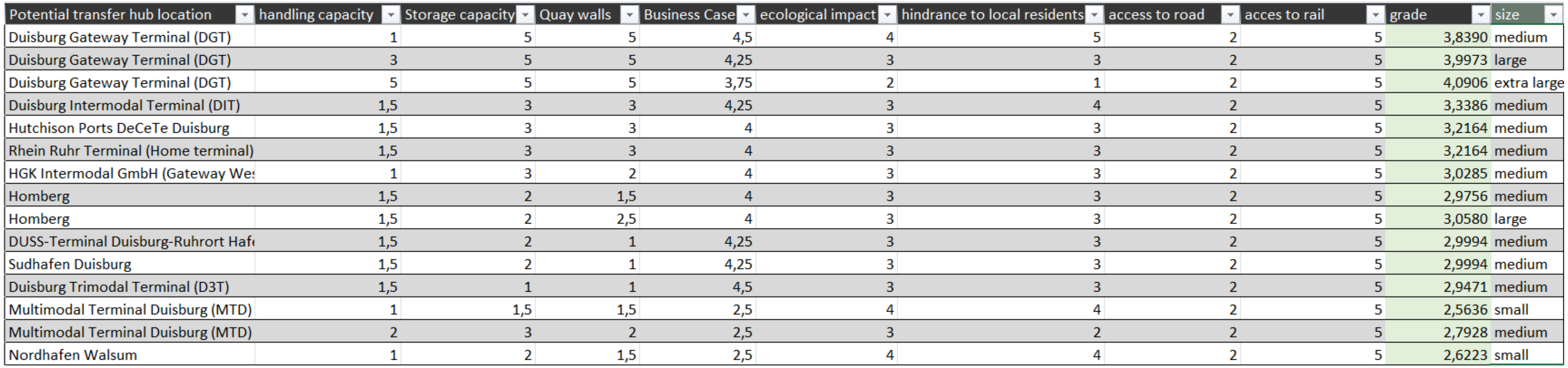
D.1. Nijmegen grading



Potential transfer hub location	handling capacity	Storage capacity	Quay walls	Business Case	ecological impact	hindrance to local residents	access to road	acces to rail	grade	size
Noordkanaalhaven	1	3	5	3,5	4	5	2	1	2,7300	medium
Noordkanaalhaven	3	3	5	3,25	3	4	2	1	2,9455	large
Noordkanaalhaven	5	3	5	2,75	2	3	2	1	3,0961	extra large
BCTN Nijmegen	1	2	2	4	4	3	2	1	2,3811	small
BCTN Nijmegen	3	2	3	3,75	3	1	2	1	2,6217	medium
BCTN Nijmegen	5	2	3	3	2	1	2	1	2,7646	large
Port of Nijmegen	3	2	2	3,5	4	4	2	1	2,7308	medium
Railterminal Gelderland Valburg	1	2	2	2,25	2	3	5	5	2,4740	small
De Beijer Groep Dodewaard	1	2	1	4	3	4	2	1	2,2714	medium
De Beijer Groep Dodewaard	3	2	2	3,25	1	3	2	1	2,3548	large
Druten Wijgula B.V.	3	2	2	2,5	2	3	1	1	2,2106	medium
Deelens transport Waalbandijk	1	2	2	3,25	3	3	2	1	2,1017	small
Ravestein B.V. Deest	3	3	2	2	1	2	2	1	2,0901	large
River Harbour Waalbandijk	3	2	2	2,25	1	2	2	1	2,0378	medium
Ijzendoorn	3	2	1	2,25	1	1	1	1	1,8643	medium

Figure D.1: Nijmegen grades

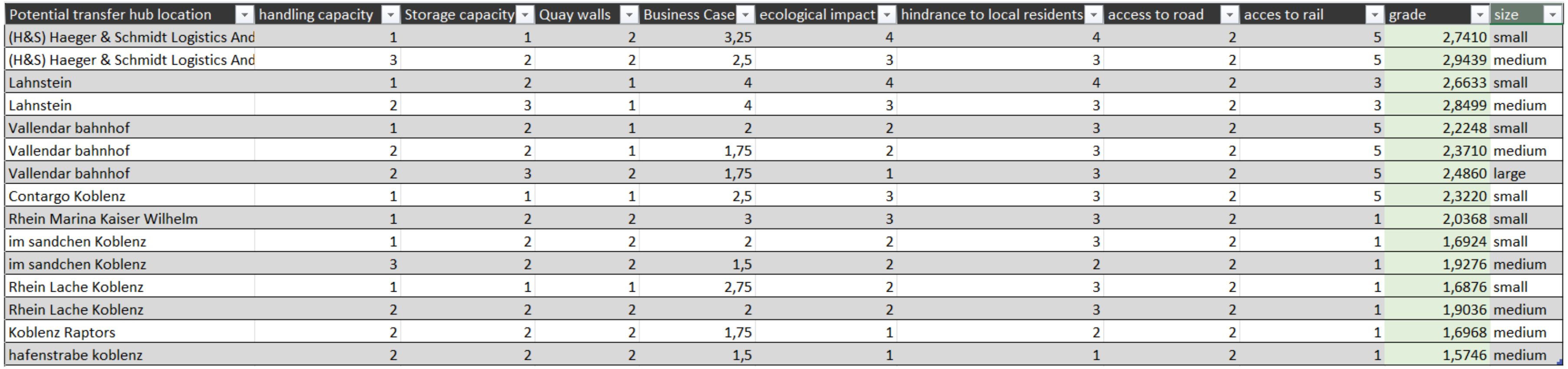
D.2. Duisburg grading



Potential transfer hub location	handling capacity	Storage capacity	Quay walls	Business Case	ecological impact	hindrance to local residents	access to road	acces to rail	grade	size
Duisburg Gateway Terminal (DGT)	1	5	5	4,5	4	5	2	5	3,8390	medium
Duisburg Gateway Terminal (DGT)	3	5	5	4,25	3	3	2	5	3,9973	large
Duisburg Gateway Terminal (DGT)	5	5	5	3,75	2	1	2	5	4,0906	extra large
Duisburg Intermodal Terminal (DIT)	1,5	3	3	4,25	3	4	2	5	3,3386	medium
Hutchison Ports DeCeTe Duisburg	1,5	3	3	4	3	3	2	5	3,2164	medium
Rhein Ruhr Terminal (Home terminal)	1,5	3	3	4	3	3	2	5	3,2164	medium
HGK Intermodal GmbH (Gateway We	1	3	2	4	3	3	2	5	3,0285	medium
Homberg	1,5	2	1,5	4	3	3	2	5	2,9756	medium
Homberg	1,5	2	2,5	4	3	3	2	5	3,0580	large
DUSS-Terminal Duisburg-Ruhrort Haf	1,5	2	1	4,25	3	3	2	5	2,9994	medium
Sudhafen Duisburg	1,5	2	1	4,25	3	3	2	5	2,9994	medium
Duisburg Trimodal Terminal (D3T)	1,5	1	1	4,5	3	3	2	5	2,9471	medium
Multimodal Terminal Duisburg (MTD)	1	1,5	1,5	2,5	4	4	2	5	2,5636	small
Multimodal Terminal Duisburg (MTD)	2	3	2	2,5	3	2	2	5	2,7928	medium
Nordhafen Walsum	1	2	1,5	2,5	4	4	2	5	2,6223	small

Figure D.2: Duisburg grades

D.3. Kaub grading



Potential transfer hub location	handling capacity	Storage capacity	Quay walls	Business Case	ecological impact	hindrance to local residents	access to road	acces to rail	grade	size
(H&S) Haeger & Schmidt Logistics And	1	1	2	3,25	4	4	2	5	2,7410	small
(H&S) Haeger & Schmidt Logistics And	3	2	2	2,5	3	3	2	5	2,9439	medium
Lahnstein	1	2	1	4	4	4	2	3	2,6633	small
Lahnstein	2	3	1	4	3	3	2	3	2,8499	medium
Vallendar bahnhof	1	2	1	2	2	3	2	5	2,2248	small
Vallendar bahnhof	2	2	1	1,75	2	3	2	5	2,3710	medium
Vallendar bahnhof	2	3	2	1,75	1	3	2	5	2,4860	large
Contargo Koblenz	1	1	1	2,5	3	3	2	5	2,3220	small
Rhein Marina Kaiser Wilhelm	1	2	2	3	3	3	2	1	2,0368	small
im sandchen Koblenz	1	2	2	2	2	3	2	1	1,6924	small
im sandchen Koblenz	3	2	2	1,5	2	2	2	1	1,9276	medium
Rhein Lache Koblenz	1	1	1	2,75	2	3	2	1	1,6876	small
Rhein Lache Koblenz	2	2	2	2	2	3	2	1	1,9036	medium
Koblenz Raptors	2	2	2	1,75	1	2	2	1	1,6968	medium
hafenstrabe koblenz	2	2	2	1,5	1	1	2	1	1,5746	medium

Figure D.3: Kaub grades

E

Extra Result Maps

E.1. Extra outputs baseline scenario results

2 Maps are also created for the ports of Antwerp and Hamburg where the transport cost per hinterland NUTS-region is shown.

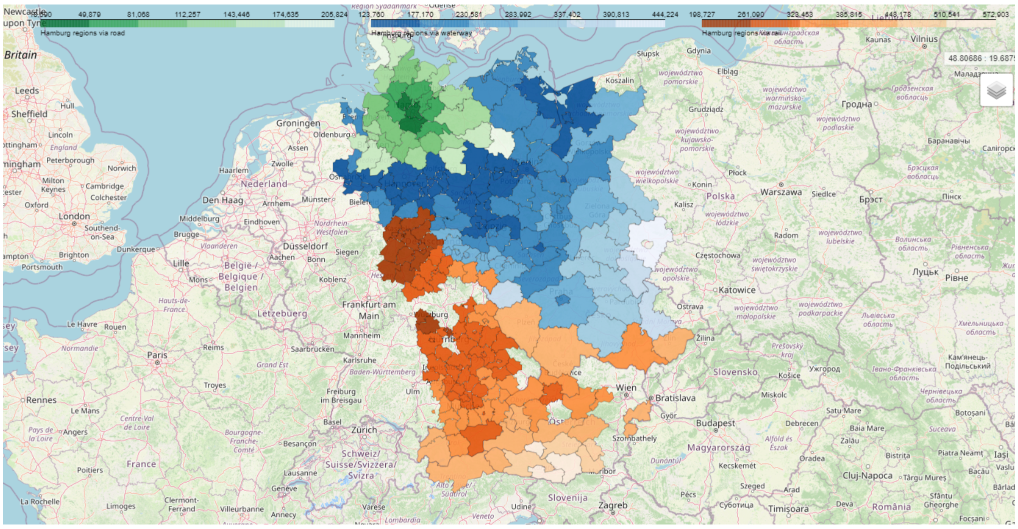


Figure E.1: Pricing modality share Hamburg for 1000 TEU

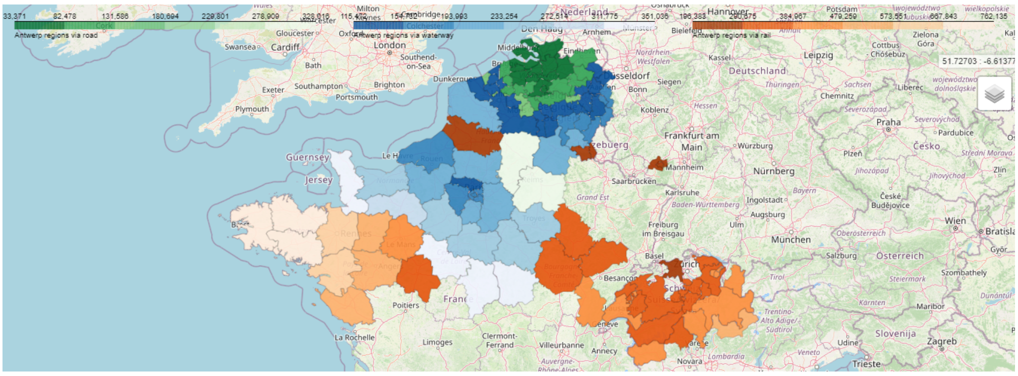


Figure E.2: Pricing modality share Antwerp for 1000 TEU

E.2. Drought scenario

E.2.1. Extra outputs drought scenario results

Maps are also created for the ports of Hamburg and Antwerp where the expansion of contested areas won by rail transport is shown. The lighter the color, the more expensive the transport costs to the NUTS-region

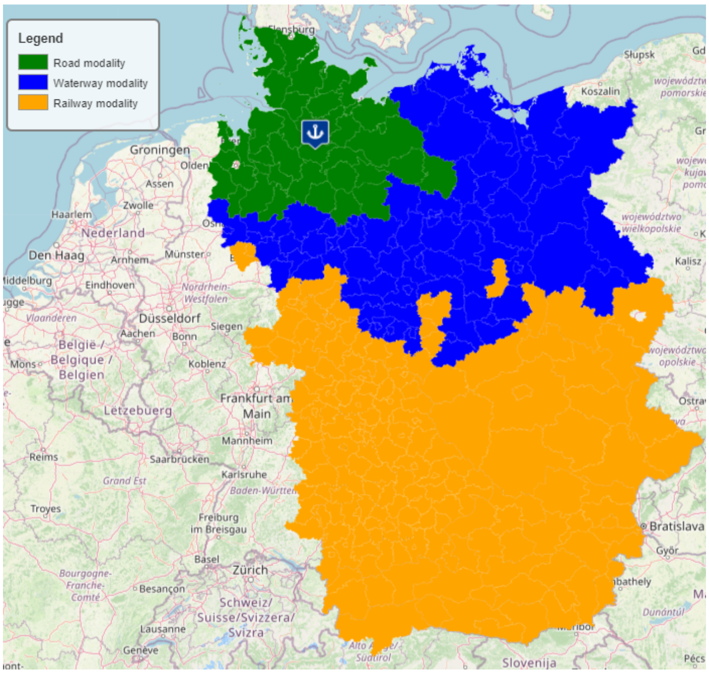


Figure E.3: Reduced modality share Hamburg during drought scenario

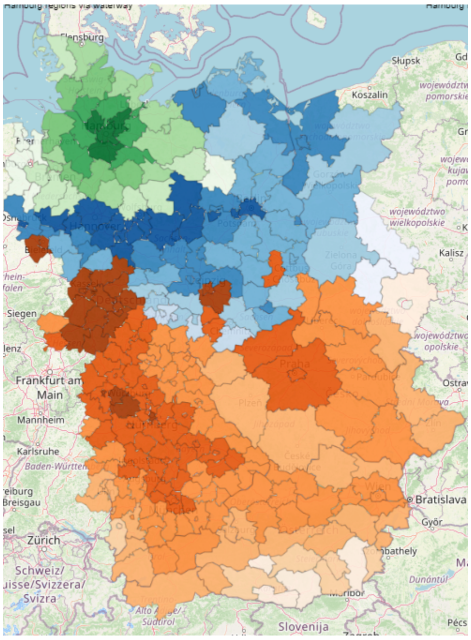


Figure E.4: Pricing modality share Hamburg for 1000 TEU during drought scenario

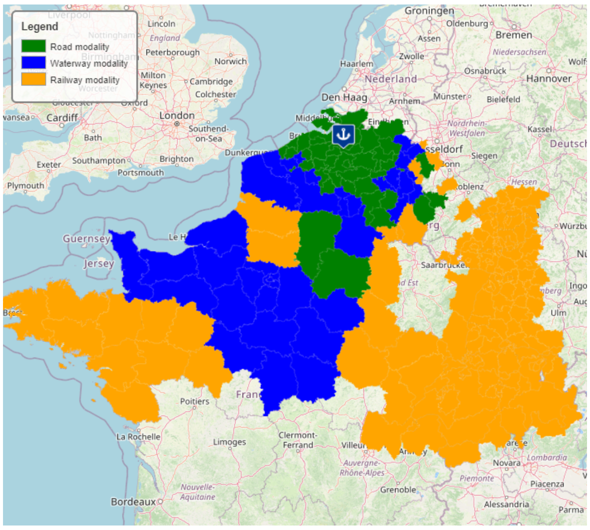


Figure E.5: Reduced modality share Antwerp during drought scenario

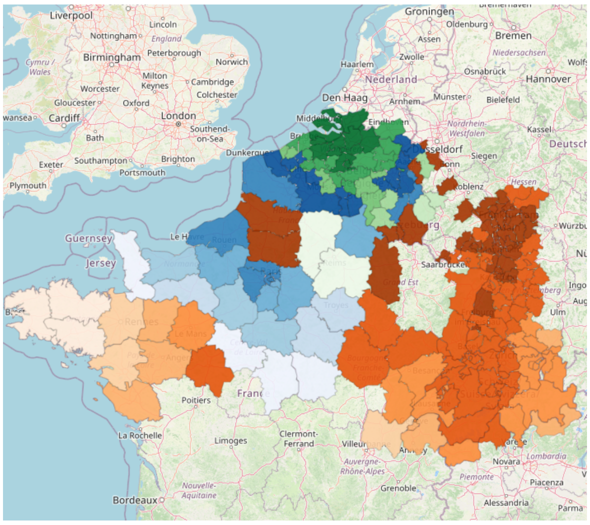


Figure E.6: Pricing modality share Antwerp for 1000 TEU during drought scenario

E.2.2. Difference Baseline - Drought scenario

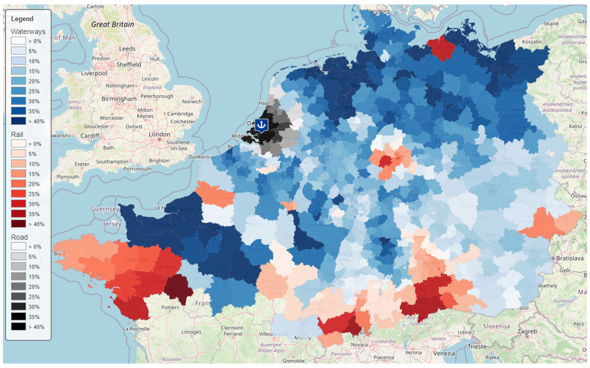


Figure E.7: Difference in modalities for the port of Rotterdam, baseline scenario

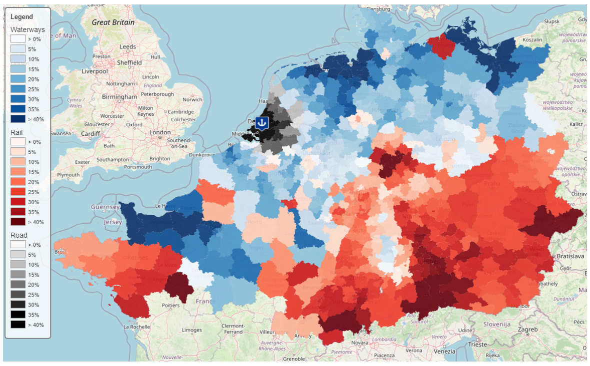


Figure E.8: Difference in modalities for the port of Rotterdam, drought scenario

E.3. Transport hubs

E.3.1. Extra outputs transport hubs

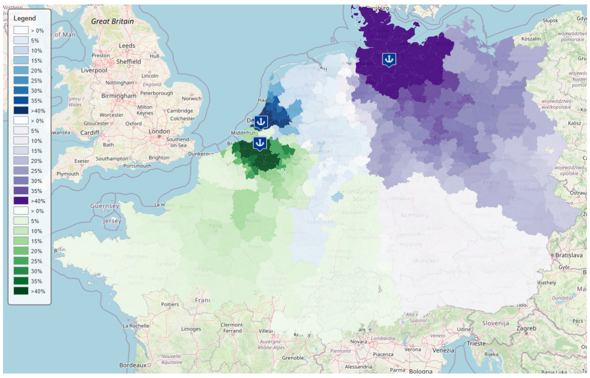


Figure E.9: Percentage difference in transport costs for 3 seaports with transport hubs assigned to port of Rotterdam

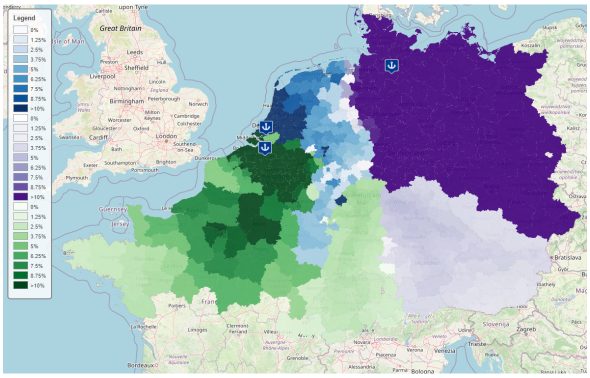


Figure E.10: Percentage difference in transport costs for 3 seaports with transport hubs, 10% maximum

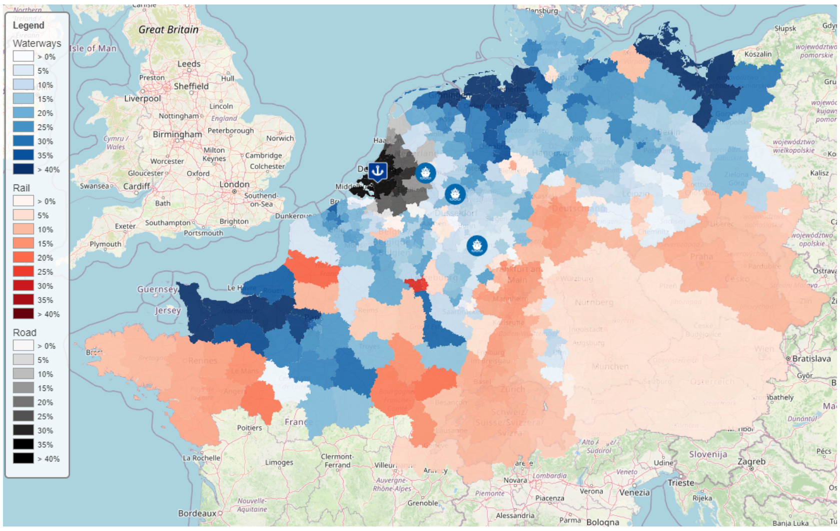


Figure E.11: Competetition between modalities from the port of Rotterdam, transport hub alternatives added to waterways

E.3.2. Modality spread of transport hubs

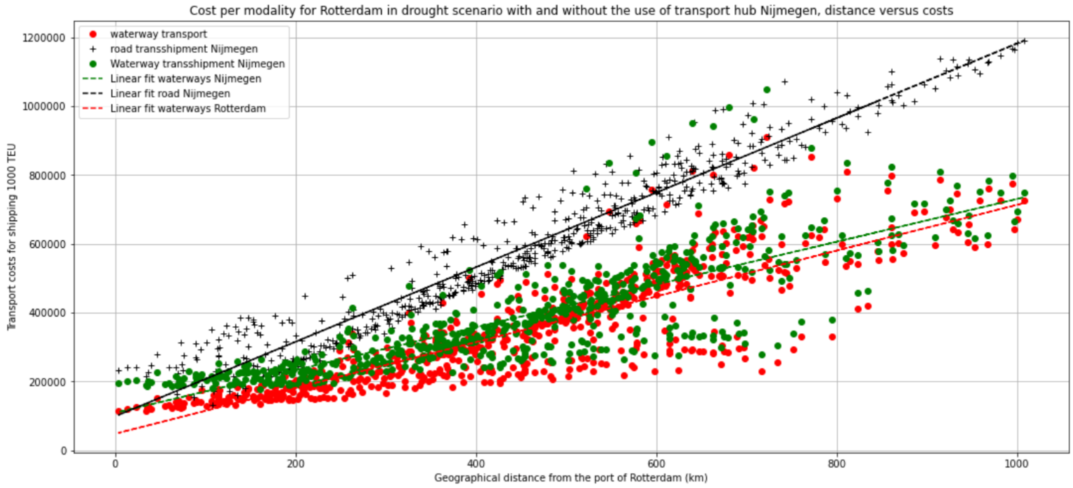


Figure E.12: Spread of cost per waterway and transport hub Nijmegen

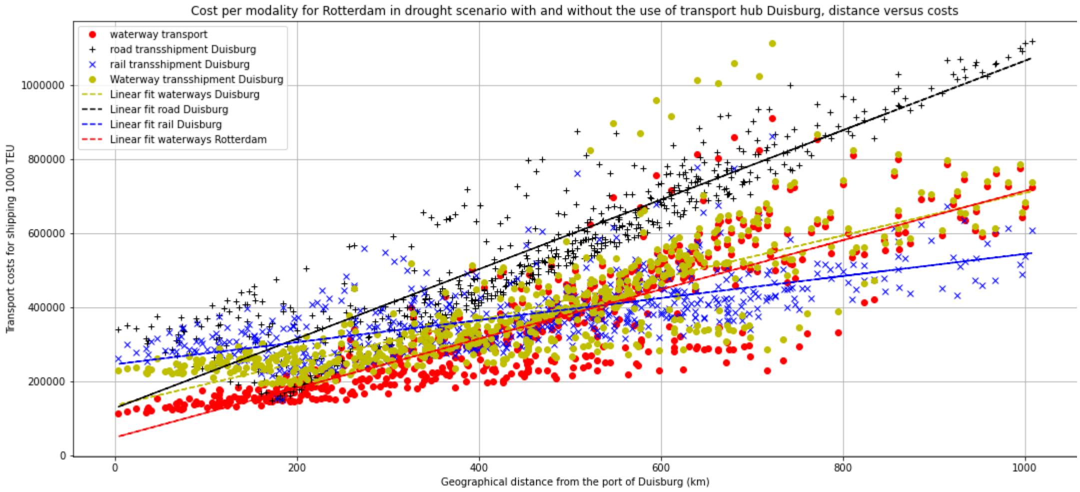


Figure E.13: Spread of cost per waterway and transport hub Duisburg

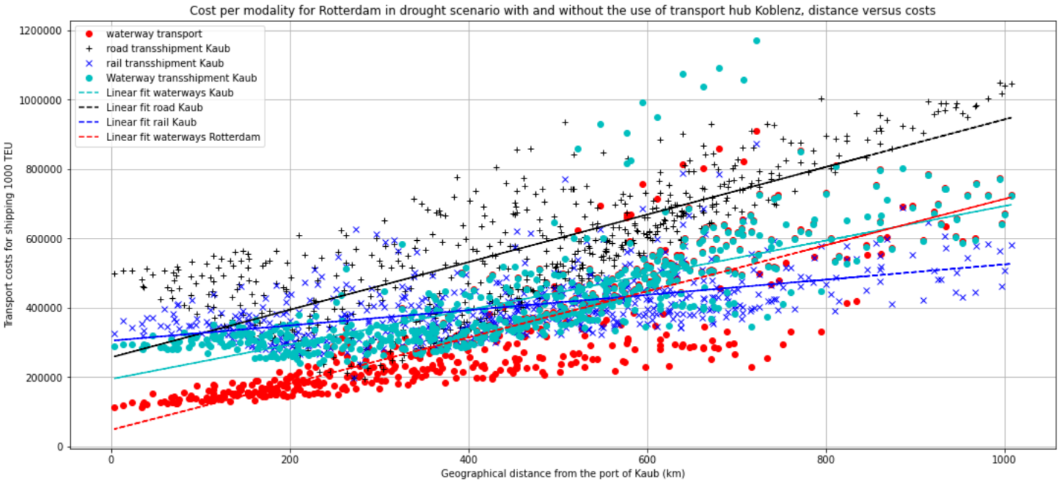


Figure E.14: Spread of cost per waterway and transport hub Kaub