Increasing Resilience in The Twente Corridor

Kimberly Tadiwanashe Mhuruyengwe | BSc Industrial Engineering & Management Science | s2276208

Increasing Resilience in the Twente Corridor
Kimberly Tadiwanashe Mhuruyengwe
December, 2024

VERSION
Version 1

AUTHOR
Kimberly Tadiwanashe Mhuruyengwe

EMAIL
k.t.mhuruyengwe@student.utwente.nl

POSTAL ADDRESS
University of Twente, Industrial Engineering and Management
PO Box 217, 7500 AE Enschede
Tel. +31(0)53489911

UNIVERSITY SUPERVISORS
1st supervisor: Dr. J.P.S. Piest
2nd supervisor: Dr. M. Koot

PORT OF TWENTE SUPERVISOR
A-R. Scheijgrond

WEBSITE
www.utwente.nl

FILENAME
BSc Thesis Industrial Engineering and Management Science

Preface

Dear Reader,

I have done this thesis project as a final assignment of my BSc of Industrial Engineering and Management Science at the University of Twente. I worked with the Port of Twente and used case studies from members of the Port of Twente, namely Combi Terminal Twente, ForFarmers and Peterson.

Firstly, I extend heartfelt gratitude to my family for supporting me emotionally and financially throughout my studies. I thank my mom, sister and my friends for their feedback, motivational support, for sitting with me through long days and nights, and their open doors whenever I needed company and any help.

I want to thank my supervisor at the Port of Twente. Anne-Ruth Scheijgrond was a great connector and source of knowledge, offering invaluable assistance, and answering my questions as soon as she could. I extend thanks to Bart Spann and Bertrand Oomen from Combi Terminal Twente, the interview and tour at the terminal was super insightful and inspiring to see the logistics of container shipments firsthand. I also thank Corne Romijn from ForFarmers and Berend Lensen from Peterson for providing information for the dry bulk case study.

Finally, much thanks goes to my academic supervisors, Dr. Jean Paul Sebastian Piest and Dr. Martijn Koot. Meeting with them was always a pleasure and I appreciate how open they were to my questions no matter how small. Their feedback was greatly detailed, having an immense impact on the quality of my thesis. Being under their supervision has been an honour and I am proud to have done this research topic as it has the potential to positively impact inland waterway logistics in the Twente region.

Kimberly Tadiwanashe Mhuruyengwe

1^{st} of December 2024

Management Summary

Research summary

This study investigated how to increase resilience in the Twente corridor when the waterways are threatened by climate stress. The research method for this investigation was using simulations to propose resilience-building strategies that would improve inland shipping performance in the corridor when faced with environmental disruptions such as drought or flooding. The Port of Twente, a critical logistics organisation, plays a vital role in this corridor, and its operations promote economic resilience and growth in the Twente region.

Problem statement: The Twente Corridor has encountered significant disruptions due to low and high water discharge extremes, which impacted the navigability of shipping vessels and caused delays at critical points like bridges and locks. The corridor's efficiency was reduced due to these disruptions, which therefore weakened the corridor's role as a sustainable logistics route. The main problem was the need for more resilient logistics management strategies that would have aided in adapting to these challenges, as opposed to embarking on costly infrastructure overhauls.

Objective: The aim was to evaluate the impact of climate-induced water level extremes on shipping performance and to propose resilience-building strategies based on the evaluation. By using a digital twin model of the Dutch waterways that was developed by Deltares, the simulations replicated shipping conditions for container and dry bulk shipments under normal, low, and high water conditions.

Research Approach: The study used simulation methodology and descriptive analysis to evaluate key performance indicators, namely transit time, loading time, vessel utilisation, and energy consumption. Real-world case studies from industry partners of the Port of Twente provided information for the model's input data, with scenarios simulated for different kinds of vessels, cargo loads, and environmental conditions.

Key findings:

1. Ship transit times increase significantly when the corridor experiences high water levels, with larger vessels experiencing the most delays.
2. Vessel utilisation is highest under low water levels due to the need for smaller vessels, while high water levels indicated an underutilisation of larger ships likely due to safety clearance limiting the vessels' cargo capacity.
3. Energy efficiency was the poorest under high water levels, as larger vessels consumed more energy per kilometre.
4. More trips, meaning more vessels, were required to transport the same throughput of cargo under low water levels due to using smaller vessels.

Proposed strategies for the consortium formed by Port of Twente:

1. Prioritise vessel classes under different water level extremes, dispatching M6 vessels when the corridor experiences low water conditions as a way to ensure navigability, and maintaining larger vessel utilisation when possible during high water conditions, particularly M9 vessels if available.

2. Optimise vessel scheduling to improve vessel utilisation rates, therefore improving fuel efficiency by maxing out vessel utilisation with every shipment, and lowering the number of unnecessary trips.
3. Implement dynamic route scheduling when possible based on real-time water level data, allowing for enhanced fleet and route adjustments to reduce bottlenecks.

To conclude, this study contributes to a broader resilience toolbox and resilience framework for inland shipping in the Rotterdam-Twente Corridor that can be applied to corridors alike. Recommendations for future work include testing the entire catalogue of vessel types classified in the digital twin model, extending the digital twin model to include more detailed operational data, and to investigate priority scheduling rules for the waterway system.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AIS – Automatic identification system
BMP – Barge Master Plan

CTT – Combi Terminal Twente
FCFS – First Come First Serve
HaMIS – Harbour Master Management Information System
IL – Inland Links
IWT – Inland waterway transportation
KPI – Key Performance Indicators
NAP – Normaal Amsterdams Peil
RIS – River Information Systems
SSP – Smart Shipping Program
TEU – Twenty-foot equivalent unit

Concept definitions

Joint Corridor: A joint corridor is a partnership between companies that are in close proximity with one another and utilise the same transport routes, i.e., the same start and end destination or vice versa. A joint corridor has a set of modalities that are set in place, e.g., barge, truck, or rail (Redactie, 2023).

Twente Corridor: A joint corridor whose defined modalities are barge and truck, with its starting/ending point the port of Rotterdam and ending/starting point Twente for the transportation of freight (Redactie, 2023).

1. Introduction

1.1. Context

Inland waterway transportation (IWT) is an essential form of transport for the movement of goods. This mode makes use of navigable rivers and canals to connect sea ports with industrial and logistics hubs established inland. For example, in Europe vital waterways like the Rhine, Meuse, Danube, and Dutch canal networks are crucial for connecting the North Sea's maritime ports to inland terminals. This modality is typified by its sustainability, cost-efficiency, and ability to hold high volumes of freight over vast distances (Vinke et al., 2024).

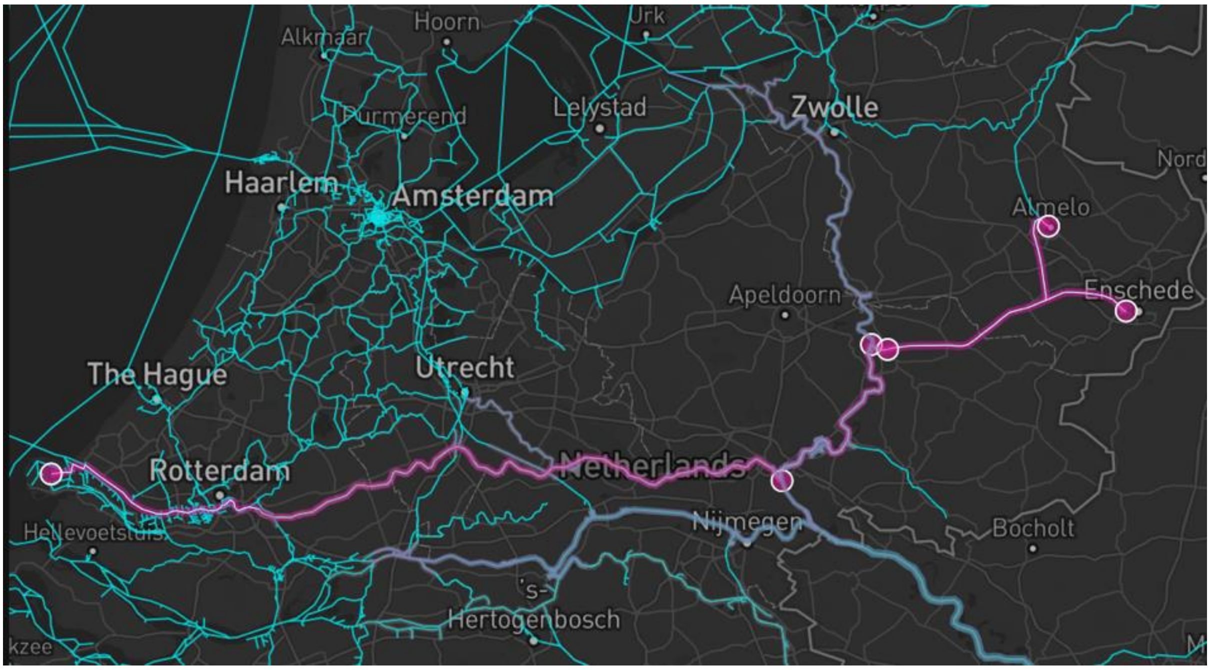
However, inland waterway transportation and logistics are becoming more vulnerable to climate stress. Climate stress alludes to the environmental pressures due to climate changes, which include extreme weather events, temperature shifts, and especially the variations in water levels due to droughts and flooding. Inland waterway transportation is directly affected by climate stress when it alters discharge rates, the flow rates of water in rivers measured in cubic meters per second. Water levels are regulated by discharge rates, and these are important for navigability. Low discharge rates can result in water levels that are too low for vessels to navigate, while high discharge rates can result in too much water that leads to flooding risks and limits bridge clearance (Vinke et al., 2022; van Dorsser et al., 2020).

The performance of inland waterway transportation is highly dependent on the performance and reliability of the inland waterways, which are highly dependent on discharge rates to maintain enough water for vessel navigation. Prolonged drought leads to reduced water depth, forcing vessels to reduce the volume of cargo they can carry to maintain a navigable draft. Conversely, intense rainfall or upstream flooding causes high water conditions, resulting in excessively high discharge rates that raise water levels in waterways, thus creating navigational hazards by limiting vertical clearance of vessels, and aggravate delays at locks and other important infrastructure along the waterway. As extreme weather patterns continue to be driven by climate change, both water level extremes are expected to be more frequent and severe in nature, making the development of resilient strategies for inland waterway operations a necessity (Holling, 1973; Zhou et al., 2019).

1.2. Port of Twente and the Twente Corridor

An important stakeholder of this research is the Port of Twente, a cooperation of transport and logistics entrepreneurs in Twente, governmental and knowledge institutions (Port of Twente: Logistieke Hotspot in Europa | Port of Twente, n.d.). An aim of the Port of Twente is to bolster the region's economic structure by strengthening water transport, therefore giving rise to the Twente Corridor (Babiche, 2023). Additionally, Babiche (2023) states that the Twente Corridor is the first joint corridor in Overijssel and is also aimed at encouraging more companies to use inland shipping between Twente and Rotterdam. The Editorial of the "Binnenvaartkrant" (2023) describes a joint corridor as a goods transit route that links multiple enterprises that share similar goals, sharing the same origin and destination.

Figure 1 - Map of the Twente Corridor



Of particular concern is the performance of inland shipping on the Twente Corridor when it is affected by disruptive events caused by climate change. The disruptive events in particular include drought and flooding indicated by extreme low water discharge rates and extreme high water discharge rates, respectively. These events expose weaknesses of the corridor and negatively affect the corridor's performance, stakeholders of the corridor, and the environment. Severe disruption of the inland shipping corridor occurred in 2018 and 2022 due to prolonged droughts. As a result, navigability of the Twente canals drastically decreased, causing millions of euros in losses for companies whose supply chains depended on inland waterway transportation. Such disruptive events indicate that the Twente Canal's supply chains are not resilient. Supply chain resilience can be defined as the capability of a supply chain to withstand, adapt, and recover from disruptions (Hosseini et al., 2019).

Although it is costly to change the physical infrastructure of the corridor, efforts can be made to redesign the logistics system for the purpose of creating a corridor that is climate-adaptive, resilient, and synchromodal. In addition, inland waterway transport is a $CO_2 -$ efficient transportation mode per tonne of goods being transported, therefore, it plays a major role in sustainable development within supply chain networks and transportation. Therefore, this study will contribute to a resilience toolbox that aims to support companies in the region to collaboratively and individually develop a resilient corridor by designing data-driven, simulation-based resilience strategies. We will use two case studies from industry partners within the Port of Twente cooperation for the simulations. These include an intermodal transport company with container terminals located in Hengelo, Almelo, and Rotterdam, and an international livestock feed company that outsources their inland shipping of bulk goods to a logistics service provider.

1.3. Problem Statement

Inland waterways facilitate the transportation of goods in containers or the transportation of liquid/dry bulk. The case studies that were chosen focused on container shipments and dry bulk shipments. Interviews were conducted to identify the problem(s) faced by inland shipping service providers that are industry partners of the Port of Twente cooperation. With respect to container transportation, companies that offer this form of service conduct daily departures to and from Rotterdam. Inbound containers arrive from the ocean on container ships at the Port of Rotterdam and are offloaded at a seaport container terminal. An inland shipping barge is scheduled to pick up the containers and ship them to an inland container terminal of an inland shipping service provider. With the current digital systems available to provide comprehensive real-time traffic intensity data at ports and at locks along the inland waterways, e.g., AIS, RIS, HaMIS, SSP, BMP, and IL, scheduling challenges still arise for management because not all waterways have automated lock management systems that share real-time traffic information. Additionally, dynamic real-time traffic information may not always be available or accurate for ships scheduled to depart from the ports or terminals, therefore, waiting times at locks are sometimes predictive and based on schedules or historical data. When there are water level extremes in the corridor, scheduling becomes more uncertain due to an increased waiting time at locks because there may not be enough water for transits, a challenge for ships transporting dry bulk, or there may be too much water for transits, a challenge for ships transporting stacked containers of multiple levels. Furthermore, during the interviews it was highlighted that once a barge is on the river IJssel, there is no longer the possibility of slowing down or returning to the port in Rotterdam to take a different route through Amsterdam, even when the manager eventually finds out there is a long waiting time at the lock at Eefde, the entrance to the Twente canals.

The problem addressed in this paper is **the investigation of the effects on inland shipping performance when the Twente corridor is faced with water level extremes and how these findings can help stakeholders in the region increase their resilience**.

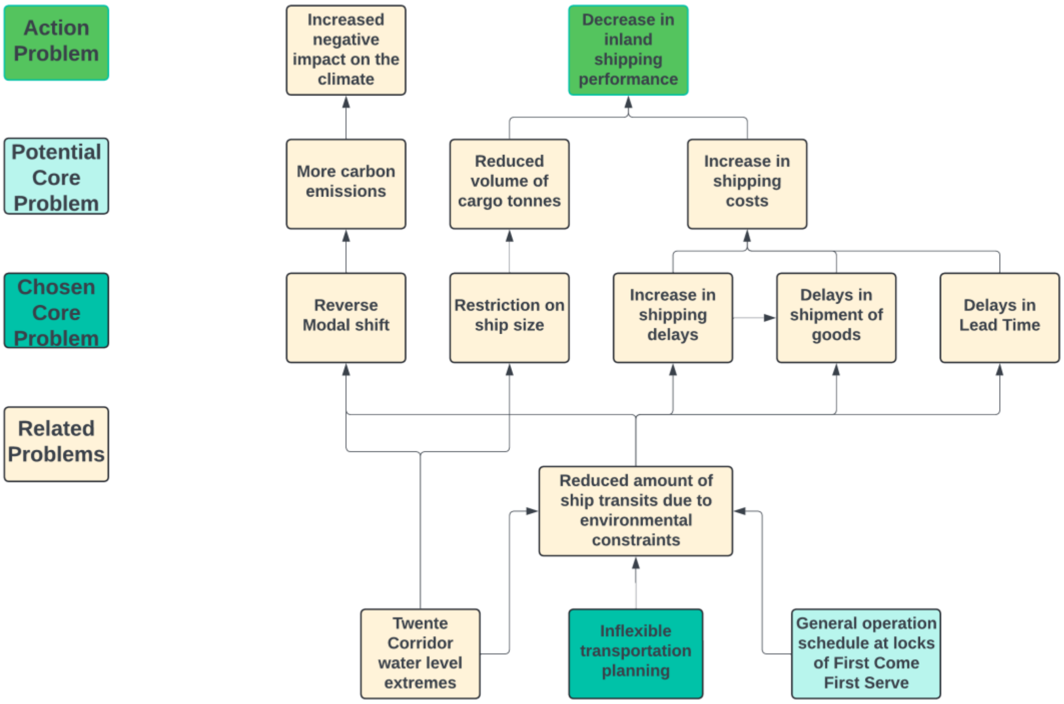


Figure 2 - Problem cluster

Water level extremes in the Twente Corridor negatively affect inland shipping performance by creating several problems, such as reverse modal shift, a phenomenon described by de Leeuw van Weenen et al. (2019) as the shift of freight flows from rail and inland shipping back to the road, resulting in a decrease in the volume being transported by water or rail, an increase in time delays, and a decrease in quality road transportation due to more congestion. The above problem cluster illustrated in Figure 1 is a flow chart concisely depicting a series of other related problems. These issues stem from the corridor experiencing water level extremes due to climate change, but most importantly, the chosen core problem is that transportation planning is not flexible, therefore leading to a decrease in inland shipping performance. Climate stress places pressure on the supply chain of the corridor, leading to multiple types of delays, a decrease in shipping volume, and an increase in shipping costs. This leads us to try and find strategies to increase the corridor’s resilience.

Inland shipping performance depends on normal water levels and a First Come First Serve (FCFS) scheduling system when making transits through the Twente Corridor. In the situation of a long waiting time to pass through locks due to water level extremes, having heavier, slower vessels ahead of lighter, faster vessels may not be ideal for both parties because this system currently causes long transit delays for all parties. There is currently no real-time accurate way of knowing delay times when transiting through the corridor; therefore, companies are making decisions only based on historical data. A tool that can potentially predict situations of delays on the corridor is a digital twin for Dutch waterways created by Deltares. Busse et al. (2021) state that digital twins are usually made for improving individual components or a supply chain rather than the entire chain. They further describe a digital supply chain twin as a dynamic model that mirrors the physical logistics system; therefore, the digital twin for Dutch waterways is a model that mirrors the physical waterways as well as the basic logistics associated with inland shipping and can help us improve this crucial component of the supply chain. With respect to the research assignment at hand, **the norm for the inland shipping performance would be identifying strategies to increase resilience under varying shipping scenarios for shipping vessels departing from the port in Rotterdam and making their way to the terminals in the Twente canals**. In summary, the research problem seeks to use simulation as a research method that can digitally carry out shipping scenarios for investigating ways to improve transportation planning, making planning more flexible, particularly when the corridor is faced with extreme water level conditions.

1.4. Research Design

The objective is to evaluate the effect of changing shipping strategies on inland shipping performance when simulating inland waterway transportation with the aim of bolstering resilience in the Twente Corridor. An analysis of simulation results will foster an understanding of how factors such as ship draft, cargo type, ship type, cargo load, loading/offloading times, and sailing speeds affect performance during climate stress.

The specific objectives addressed in the rest of this study include:

- Simulating shipping scenarios based on case studies for both container and dry bulk shipments and performing a comparative quantitative analysis on their performance metrics under low and high water conditions.
- Recommending how managers of inland waterway services can implement these results as guidelines to ensure resilience and efficiency in the Twente Corridor under varying water level conditions.

Key deliverables will include a report on adaptive strategies that will provide a structured approach to manoeuvring limitations on inland shipping, a simulation analysis using the digital twin whose results will be documented in this report and will be used as the foundation for developing the strategies, and finally, recommendations for implementation and further research.

This study seeks to answer the following main research question:
How can the <u>impact of water level extremes</u> on <u>resilience in the Twente Corridor</u> be determined through <u>simulation</u>?

The problem-solving approach is based on the simulation procedure proposed by Robinson (2014). This procedure follows four phases, namely understanding the problem, conceptual modelling, computer modelling and understanding and implementing the results. Furthermore, to gather the information required to find solutions to the main research question and to guide the research process, the following sub-research questions are investigated at each phase of the simulation methodology.

Phase 1: Understanding the (real world) problem

The previous section has already elaborated on the problem at hand; therefore, the efforts in this phase will focus on having an in-depth understanding of how the shipment process works in the Twente Corridor. This understanding will aid in the data gathering process and how to setup experiments that will output useful results for future decision-making. As a result of this phase's intentions, the research design for the related research questions will be exploratory in nature.

1. **Research question**: What are the current inland shipping processes for containers and dry bulk freight?
2. **Research question**: What are the current metrics and their measurements for indicating performance-based resilience of a logistics corridor?

Understanding what type of input variables the digital twin needs when running experiments will be crucial for choosing which key performance indicators will be used to track inland shipping performance; therefore, a process flow chart of the shipping processes will lay a good foundation for modelling experiments, therefore making the use of the digital twin more effective.

Phase 2: Conceptual Modelling (data gathering)

Robinson (2014) describes the process of "abstracting a model from a real or proposed system" as conceptual modelling. In this phase, the focus is obtaining an understanding of how the digital twin model facilitates an abstraction of the real Twente Corridor. This phase will explore important concepts and objects represented in the model.

3. **Research question**: What are the key concepts and objects that interact with the shipping vessels to create an abstraction of the real world shipping process?
4. **Research question**: What key performance indicators (KPIs) are relevant to performance-based resilience in a simulation study of a waterway corridor?

Phase 3: Computer Modelling and Validation

Within this phase, one of the goals is to document the use of the model since the digital twin model is already available to use. Robinson (2014) states that aside from model development, it is important that stakeholders of the simulation study receive model documentation; that way, stakeholders and future users of the model are able to understand how the model works when using it and when interpreting the results. Another goal is to verify and validate the model of this study using Black-box validation, a form of validation that compares the simulation model to the real world (Robinson, 2014). This means that to place confidence in the model, the model should have sufficiently similar results to the real-world system when run under the same conditions. The following research questions guide the documentation of the model:

5. **Research question**: How does the model use key variables to represent the effects of low and high water levels on the navigability of different ships in the Twente Corridor?
6. **Research question**: How does changing vessel characteristics and water discharge rates affect key performance indicators generated by the digital twin model?
7. **Research question**: How closely do the model's results of transit times under normal, low, and high water conditions align with historical shipping data for the Twente Corridor?

Phase 4: Understanding and Implementation

Implementation of the model can take the form of implementation that leads to a deeper understanding of the real world from a results from simulation experiments perspective and a usage of the model perspective. Similar to the case of the Deltares digital twin model Robinson (2014) rightly points out that a simulation model is designed to help users make recurring decisions, like in the case of this study deciding on a scheduling strategy. Therefore, understanding the capabilities and use cases of the simulation model can lead to a transformation in management strategies. The following research questions direct this phase to highlight two forms of implementation, namely implementation as learning and implementing the model for decision-making:

8. **Research question**: What do the results from the simulation experiments suggest to be the evaluation criteria and implementation plan of new methods for increasing resilience in inland shipping during water level extremes?

1.5. Thesis Structure

The remainder of the paper is organised as follows: the methodologies for the systematic literature review and the research process are elaborated in Chapter 2, and the literature review is introduced in Chapter 3, which includes the main research framework and metrics of resilience. In Chapter 4, the paper will provide an understanding of the "real world" problem. This is followed by Chapter 5, wherein the Twente corridor is conceptualised to better understand how the Deltares digital twin model relates the various concepts and variables in the simulation model, including the data processing method to quantify resilience indicators. Additionally, the application of this simulation model will be conducted in Chapter 6. Finally, a discussion of the results and conclusions as well as recommendations for future work are discussed in Chapter 7.

2. Methodology

This section provides a general overview of the literature review methodology and the research methodology used for this research. As previously mentioned, simulation methodology was adopted for this study and consists of four different phases. First in chapter 2.1 is an explanation of the systematic review methodology used for identifying relevant literature to support this study, and next in chapter 2.2 is an explanation of how the research process was mapped to the different phases. Finally, chapter 2.3 goes over the scope and limitations of the research methodology.

2.1 Literature review methodology

Within the research design, the main research question and associated knowledge problems were established as a guide for the study. From the main research question and the problem statement stated in the introduction chapter, the main concepts that make up the theoretical framework of the study were used to create a search matrix, which can be found in Appendix C. The search matrix was used as a repository of the main terms and the various forms and synonyms that they could take within relevant literature. Thereafter, a list of scientific databases to conduct the systematic search was made based on the ease of use and known availability of journals and articles within the field of study. Inclusion and exclusion search criteria were defined and can also be found in Appendix C, placing an emphasis on the use of literature published in English, the timeline, and the discipline specific to logistics management and engineering. It was also important to exclude any literature that was not peer reviewed and had nothing to do with simulation or inland waterways.

The next step was creating search queries and then tracking the literature search process by using a search log. This search log can also be found in Appendix C. After reading the title and abstracts of relevant literature, a reference manager was used to keep track of all the papers gathered. Subsequently, the final step of the systematic literature review was the process of elimination. This process is illustrated in the screening flow chart found at the end of Appendix C. This process consisted of reading through the papers, identifying key methods used in the literature, knowledge gaps, and reading over the discussion of the results. Other relevant literature was found by looking through the references of papers found during the systematic search. Altogether, this method of identifying relevant literature for this research gave way for an extensive discussion about the theoretical framework of this study, expanded upon in Chapter 3.

2.2 Research Methodology

As it would be too costly and impractical to re-engineer the infrastructure of the corridor to make inland shipping feasible even under climate stress, Segovia et al. (2022) suggest another strategy is planning the corridor's lock operations to maximise vessel passage efficiency. Rather than viewing the problem as an optimisation problem as did Segovia et al. (2022), this study approached it from a descriptive analysis perspective, focusing only on the development of shipping strategies that can improve the operational efficiency of ship transits under varying water conditions.

Simulations were applied to identify patterns in transit times, cargo loading times, and other factors affecting inland shipping performance. Simulations were run on a digital twin for Dutch Waterways created by Deltares (Deltares-Research, n.d.), therefore a model did not have to be made from scratch. Currently, the tool mirrors the physical waterways and logistics processes of inland shipping by simulating shipments of various ship types transporting either containers or dry bulk and how they perform under different conditions such as low water, normal water, and high water. Additionally, it can simulate how different ships interact with key elements of the corridor's infrastructure, such as bridges and locks.

This descriptive approach did not try to optimise every individual ship's transit but focused on developing practical, flexible strategies that could be adapted to real-world scenarios. The findings will act as a guideline for the logistical planning of cargo transportation from the ports and terminals when under extreme water conditions.

Firstly, the understanding the "real world" problem phase focused on gathering data to understand the shipping processes in the corridor based on the practices of the companies used as case studies in this research, as well as to identify their pain points when water level extremes would occur. The data gathering method in this phase was through conducting interviews with representatives from all three companies. To document the processes, business process modelling was used as a method to visually represent the shipping processes, making it easier to model the simulation experiments.

In the conceptual modelling phase, based on the understanding of the "real world" problem and the digital twin tool, a representation of the main constituent elements that interact to create the Twente corridor was modelled. The abstraction was also used to explain the relationships between the various concepts that are modelled by the digital twin, as well as identify the input variables that were required to create the research experiments. Both of these knowledge points, together with a literature review, aided in the process of identifying the important output variables whose metrics were used as the key performance indicators. Data was gathered by receiving historical shipping data from the companies involved in this study. With this data, initial control experiments were run to understand how the digital twin operates and to identify which input variables had vital influence on the output variables as per the scope and objective of the study. This phase established the control variables and the variables that could be manipulated.

Subsequently, in the computer modelling and validation phase, by way of literature review and data aggregation of historical shipping data, settings and values for the input variables were defined, as well as the number of experiments needed for each water level condition and shipping scenario made up of cargo tonnage and ship variation. Experiments were run twice to ensure construct validity of the model, and the results of the transit times from experiments under normal, low, and high water levels were compared to the real-world shipping transit time to ensure the model's overall validity.

Finally, the understanding and implementation phase was simplified to interpreting the results of the simulations and using these findings to create an implementation plan under each water level condition for both container and dry bulk shipments based on the evaluation criteria, namely the key performance indicators.

2.3 Scope and Limitations of Research Methodology

With a focus on improving resilience of inland shipping in the Twente Corridor under low and high water conditions, discrete event simulation is the best form of simulation methodology to mimic the process of the shipping freight, defining the arrival and departure of ships into or out of the corridor as events and the number of ships transiting the corridor over a period of time as the state. Additionally, the scope of this study is centred around the Twente Corridor and does not extend to other waterways or other modalities, therefore constraining the generalisability of the results. Furthermore, the scope is further defined by using the digital twin model as a simulation tool that can give detailed and specific insights into the Twente Corridor, although it may not capture all the nuances of real-world shipping operations because of the model's inherent simplifications.

With respect to the limitations of this study, firstly, the reliability of the results from the experiments largely depends on the accuracy and wholeness of the input data provided by the stakeholders of this study. Misleading results can arise from any inaccuracies in the datasets provided, especially with respect to the effectiveness of the priority scheduling rules that will be proposed in the discussion and conclusion of this study. Secondly, even though the model has great detail, it still harbours simplifications or real-world dynamics, such as leaving out other dynamic operational conditions. Discrepancies between the actual shipping performance and the simulated results arise as a result of these simplifications. Additionally, the digital twin model does not take into account unexpected external factors such as economic fluctuations, infrastructure developments, and changes in policy, all of which could impact how valid the results will be. Finally, there is the limitation that although the digital twin model is advanced, it itself has limitations in accurately replicating every feature of the physical and logistical environment, particularly under extreme conditions where, in reality, system behaviour becomes unpredictable.

3 Literature Review

In the systematic literature review, key concepts that make up the theoretical framework of this research study are explored and elaborated upon. The method of a systematic review provides a comprehensive summary of state-of-the-art practices, policies, and knowledge of the waterway transportation industry, identifies research gaps, and provides evidence to support claims within this study. Appendix C provides a comprehensive analysis of the systematic review process. The systematic review focuses on the key concepts identified in the problem statement and main research question, which include inland waterway transportation and logistics corridors discussed in Section 3.1 together with climate stress, resilience in transportation discussed in Section 3.2, and simulation using digital twins, concluding the literature review in Section 3.3.

3.1 Inland waterway transportation, logistics corridors and climate stress

It has previously been observed that climate stress, in this case in the form of water level extremes, has had effects on the performance of inland waterway transportation and logistics corridors; therefore, these two themes will be explored in tandem to identify what current research has discovered.

Inland waterway transportation is described by Vinke et al. (2022; 2024) as an important mode of freight transport, especially in the Rhine, Europe's busiest waterway, and its tributaries. This modality has a vital role in regional and international logistics, especially in enabling the movement of containers and bulk goods efficiently. This is a crucial mode of transport between the Port of Rotterdam and multiple inland industrial areas in the Netherlands and as far as in Germany and Switzerland, making it a vital part of the hinterland logistics corridor. These corridors, although they rely on stable water levels for navigability, bring about advantages, such as reduced carbon emissions and lower transportation costs compared to road transport.

The droughts of 2018, 2019, and 2022 exhibited the Rhine's weakness, and as such, its tributaries like the IJssel, to low-discharge extremes, and demonstrated the negative impacts on the corridor in the form of considerable supply chain disruptions (Vinke et al., 2024). It should be noted that floods can also have a significant impact on the corridor. To expand further, a particular form of disruption identified by Vinke et al. (2022) and van Dosser et al. (2020) is how the ship draught is affected by extreme low discharges, therefore directly affecting the cargo capacity of the ship and increasing freight costs significantly. Other operational challenges that arise due to the fluctuations of water levels are bottlenecks at locks and bridges. These bottlenecks become serious areas of congestion in waterways because of delays being exacerbated due to water level extremes, e.g., the bottleneck at Kaub, along the Rhine, where limited ship capacity led to congestion (Vinke et al., 2022; 2024). Low water levels can also limit larger vessels from navigating through some parts of the waterway. High water levels threaten navigability and safety by reducing the ship's bridge clearance.

Vinke et al. (2024) give a brief and more general answer to the first research question, explaining that "at an operational level/short-term level, ship operators need to decide how many vessels of which class they need to deploy where and how much cargo can be loaded in light of draft bottlenecks along the anticipated route." Therefore, these climate stress-induced disruptions underpin the need for resilient transport strategies. A fleet adjustment strategy is argued by Vinke et al. (2024) and van Dosser et al. (2020), such as using smaller ships with shallower drafts for low water levels. Other strategies to increase transport efficiency identified by Vinke et al. (2022) are modifying loading rates, such as loading lower levels of containers for high water levels and increasing sailing hours. Within this study, there is a contribution to known literature by focusing on the Twente Corridor, a corridor that has not been thoroughly modelled with respect to its resilience to climate stress and how climate stress affects operational efficiency in the Twente Corridor. Focusing on this region leads to an in-depth understanding of localised impacts and tailored strategies. It has previously been observed that climate stress, in this case in the form of water level extremes, has had effects on the performance of inland waterway transportation and logistics corridors; therefore, these two themes will be explored in tandem to identify what current research has discovered.

Inland waterway transportation is described by Vinke et al. (2022; 2024) as an important mode of freight transport, especially in the Rhine, Europe's busiest waterway, and its tributaries. This modality has a vital role in regional and international logistics, especially in enabling the movement of containers and bulk goods efficiently. This is a crucial mode of transport between the Port of Rotterdam and multiple inland industrial areas in the Netherlands and as far as in Germany and Switzerland, making it a vital part of the hinterland logistics corridor. These corridors, although they rely on stable water levels for navigability, bring about advantages, such as reduced carbon emissions and lower transportation costs compared to road transport.

The droughts of 2018, 2019, and 2022 exhibited the Rhine's weakness, and as such, its tributaries like the IJssel, to low-discharge extremes, and demonstrated the negative impacts on the corridor in the form of considerable supply chain disruptions (Vinke et al., 2024). It should be noted that floods can also have a significant impact on the corridor. To expand further, a particular form of disruption identified by Vinke et al. (2022) and van Dosser et al. (2020) is how the ship draught is affected by extreme low discharges, therefore directly affecting the cargo capacity of the ship and increasing freight costs significantly. Other operational challenges that arise due to the fluctuations of water levels are bottlenecks at locks and bridges. These bottlenecks become serious areas of congestion in waterways because of delays being exacerbated due to water level extremes, e.g., the bottleneck at Kaub, along the Rhine, where limited ship capacity led to congestion (Vinke et al., 2022; 2024). Low water levels can also limit larger vessels from navigating through some parts of the waterway. High water levels threaten navigability and safety by reducing the ship's bridge clearance.

Vinke et al. (2024) give a brief and more general answer to the first research question, explaining that "at an operational level/short-term level, ship operators need to decide how many vessels of which class they need to deploy where and how much cargo can be loaded in light of draft bottlenecks along the anticipated route." Therefore, these climate

stress-induced disruptions underpin the need for resilient transport strategies. A fleet adjustment strategy is argued by Vinke et al. (2024) and van Dosser et al. (2020), such as using smaller ships with shallower drafts for low water levels. Other strategies to increase transport efficiency identified by Vinke et al. (2022) are modifying loading rates, such as loading lower levels of containers for high water levels and increasing sailing hours. Within this study, there is a contribution to known literature by focusing on the Twente Corridor, a corridor that has not been thoroughly modelled with respect to its resilience to climate stress and how climate stress affects operational efficiency in the Twente Corridor. Focusing on this region leads to an in-depth understanding of localised impacts and tailored strategies.

3.2 Resilience in transportation

There is a growing body of research that identifies the need for creating strategies that allow stakeholders of inland waterway transportation systems to be resilient against unforeseen disruptions such as those caused by climate change. In this body of research, we identify the origins of resilience and its various definitions with respect to resilience in transportation and discuss proposed strategies of increasing resilience as well as research gaps in this field.

Previous research has established resilience as the ability of a system to “bounce back” from events that are disruptive and restore its functionality. Holling (1973) created a framework that introduced two major concepts, namely engineering resilience, which refers to how swiftly a system returns to equilibrium, and ecological resilience, which measures how much disturbance a system is capable of absorbing before changing state. In transportation, resilience often refers to a combination of both ecological and engineering resilience, the system’s capacity to absorb disruptions, recover from them, and ultimately continue to function at a sustainable level of service (Holling, 1973; Esmalian et al., 2022; Omer et al., 2012). In this study, resilience is not only explored in its meaning of a system absorbing disturbance and returning to a stable equilibrium but also that of a socio-technical system’s capacity to continue operating in a certain way while being directed by management or decision-makers (Wang & Yuen, 2022). Furthermore, resilience has also been increasingly portrayed as a dynamic property of systems as it involves recovery in the short term and adaptation in the long term (Hosseini et al., 2019; Omer et al., 2012). Studies by Hosseini et al. (2019) and Omer et al. (2012) have placed an emphasis in their frameworks on adaptability and not just recovery by means of incorporating concepts such as flexibility, redundancy, and robustness as components of resilience.

Multiple resilience-building strategies have been investigated. One such strategy is increasing the redundancy of resources, like having alternate waterway routes to use or having backup infrastructure such as using smaller vessels during low water conditions, or the more common practiced strategy of temporarily shifting cargo to alternative modes of transport (Wang & Yuen, 2022; Omer et al., 2012). Zhou et al. (2019) used diversification of cargo handling and infrastructure hardening to lead to better system performance during climate stress. An additional strategy is real-time resource allocation and adaptive scheduling to enable transportation systems to react to disruptions by adjusting operations in real time (Wang & Yuen, 2022; Zhou et al., 2019).

To make this strategy possible and to do so efficiently, Omer et al. (2012) argue for incorporating cross-agency collaboration, which includes coordination between shipping companies, port authorities, and local governments.

To increase performance-based resilience, it is pertinent to know how to measure performance. The second research question seeks to identify the relevant metrics for measuring inland shipping performance mentioned in literature, as well as define these metrics alongside other key performance indicators present in the digital twin model as a response to the fourth research question. Those relevant to this study are the following:

- Transit time – the total journey time completed by a vessel from origin to destination. Its measurement is in hours, based on distance and navigability (Busse et al., 2021; Smith et al., 2009).
- Vessel utilization – the vessel's capacity being used to transport cargo as a percentage. The measurement is taken by comparing actual cargo carried against the maximum load that the vessel can carry (Felde et al., 2022).
- Energy expenditure – the amount of fuel utilised by vessels. The measurement is in KWh (Desai & Prock, n.d.).
- Delay time – the additional transit time experienced by vessels when water levels are too low or too high. The measurement for this metric is in hours of additional time in comparison to the normal transit time when water level conditions are normal (Busse et al., 2021; Smith et al., 2009).

Other useful metrics that are calculated in the digital twin model are the loading time, which is the time taken for the port or terminal operators to load cargo into a vessel or unload the cargo from a vessel, and the total operating time, which is an aggregation of the transit time and the loading time. Metrics that will not be used in this study but are found in literature include vessel traffic density, recovery time of the waterway system after disruption occurs, economic costs of delays, route choice flexibility, lock passage time, and cargo throughput (Busse et al., 2021); (Desai & Prock, n.d.); (Felde et al., 2022); (Smith et al., 2009).

Within the study of resilience in transportation, a key debate is the parity between engineering resilience and ecological resilience, as some papers argue that waterway transportation systems should be focused on long-term adaptability as opposed to only returning to the state before disruption (Holling, 1973; Henry & Emmanuel Ramirez-Marquez, 2012). This study explores how proposed strategies suitable for implementation in the Twente corridor can be identified and implemented for long-term adaptability. Additionally, multiple studies foreground the lack of comprehensive quantitative resilience models for waterway transportation systems, and while there are specific scenarios such as weather disruptions that have been incorporated in models, these models often do not account for the interconnectedness of transportation networks and the butterfly effects of disruptions (Omer et al., 2012; Zhou et al., 2019). Therefore, future research calls for integrated resilience models that account for both short-term recovery and long-term adaptability. Henry & Emmanuel Ramirez-Marquez (2012) and Omer et al. (2012) call for models that should incorporate real-time data to improve decision-making during crises. Saisridhar et al. (2024) also suggest focusing future research on understanding how disruptive events in one area of the system propagate throughout the entire transportation network, as this would be essential to creating comprehensive resilience.

3.3 Simulation using digital twins

This section explores how previous research has established the use of simulation to evaluate disruptive events on inland waterway systems to create methods of quantifying resilience and techniques of increasing said resilience using models. This study more specifically explores conducting a simulation methodology using a digital twin of the waterway system; therefore, it is important to discuss the role that digital twining has within the supply chain system.

A resilience-building strategy that was used as the methodology for this research study is the use of simulation and modelling to assess the impact of disruptions on a waterway transportation system. Discrete event simulation models help to evaluate the performance of the waterway system when it is under stressful conditions, and this evaluation guides decision-making on resilience improvements (Saisridhar et al., 2024; Hosseini et al., 2019). As a broad definition, simulation is the representation of a system and its dynamic processes in a model in which experiments can be conducted upon the model to produce findings applicable to the real world (Felde et al., 2022). Within the context of this study, simulation involves the modelling of vessel moments, cargo flows, and discharge rates of rivers and connected inland waterways to understand the system’s performance under varying conditions. As previously mentioned, a digital twin will be used to run simulation experiments for this study. Busse et al. (2021) define a digital twin as a virtual representation of a physical system that imitates real-time data and can simulate scenarios, and in the case of inland waterways, a digital twin can be used to simulate a waterway transportation network and its role in supply chains, helping to make operations efficient under various operational and environmental stressors.

The primary method used to model inland waterway systems is discrete event simulation, which involves modelling a system as a sequence of discrete events such as loading cargo into a ship, a ship passing through a lock, and so on. This method of simulation allows for analysing congestion, transit times, and any bottlenecks (Smith et al., 2009; Felde et al., 2022). Desai & Prock (n.d.) highlight that discrete-event simulation is especially useful when modelling complex, interdependent systems such as inland waterways that require the coordination of locks, bridges, and vessel traffic. The digital twin in use for this study uses for its methodology source data for the network found on the vaarweginformatie site managed by Rijkswaterstaat. On this site is the up-to-date information of nearly all the Dutch waterways, the main waterways in Germany, Austria, France, Belgium, and Switzerland. This information includes characteristics of the waterways, their width, and the operating times or dimensions of locks and objects on the waterways. The data is processed to be topologically connected and to be used for transport network analysis. To further explain, the digital twin is best described as a topological network of the Dutch fairway information system. It is a graph-based representation of an inland waterway transport system, where nodes represent critical points such as ports, terminals, locks, bridges, or junctions, and edges represent the routes/fairways that were navigable between these points. This kind of network is modelled to manage the flow of vessels along the waterway system by specifying the connectivity and relations between the nodes.

Busse et al. (2021) suggest that digital twins can bolster resilience by facilitating pre-emptive identification of bottlenecks, therefore allowing adjustments in vessel scheduling to be made faster. Busse et al.'s (2021) findings suggest that digital twins can help assess various water level scenarios, making it simpler to plan for extreme conditions such as drought or flooding, therefore theoretically supporting this research study.

Regarding gaps in literature that are yet to be addressed, Busse et al. (2021) identify that although there is much potential of digital twins, integrating real-time data from various sources is a challenge faced by many current models, therefore limiting the effectiveness of these models in dynamic and interdependent systems such as inland waterways. Another gap in research that could limit the scalability of digital twins in bigger and more complex networks is the lack of comprehensive digital twins that represent entire multimodal supply chains. A strength of the digital twin used for this study is that it is nearly a comprehensive digital twin of the entire Dutch waterway network, including the Rhine corridor extending from Rotterdam in the Netherlands to Basel in Switzerland. This means users of the model can experiment on various routes and waterway scenarios to improve their operations and anticipate any mishaps. Based on the studies that have used simulation and digital twinning for monitoring and predictive maintenance of inland waterways, not many studies have concentrated efforts into using these tools to increase resilience in inland waterway transportation when under climate-induced disruptions, making this study an important work.

The main contributions of this study will be adding to the resilience framework by concentrating on operational strategies, specifically in investigating the operational effects of varying water level conditions in the Twente Corridor. Additionally, this research extends the utilisation of digital twins in inland waterway systems, integrating real-time data that creates the topological network and offers a dynamic and predictive tool for bolstering resilience under extreme conditions. Finally, the analysis of the simulation results will provide quantifiable evidence for waterway logistics on how to modify operations under low and high water conditions, therefore promoting a more efficient and resilient logistics corridor.

3.4 Summary and Conclusion

This review established the impact of climate stress on inland waterway transportation by looking into how extreme water conditions disrupt logistics corridors such as the Rhine and its tributaries, specifically the IJssel. Elaborating on the characteristics of logistics corridors relates directly to research question 1 on understanding current shipping practices and research question 2 on currently used performance metrics for assessing logistics corridors. The knowledge gathered in the literature review guides what to elaborate on further in Chapter 4. Additionally, the need for operational processes to become resilient to disruptions relates to research question 3 on the corridor’s constituent elements and how they interact in the digital twin model as an abstraction of the real system, as well as research question 4 on the relevant performance-based resilience key performance indicators to use in this study. Some but not all of the indicators found in the review return in Chapter 5 include delay times, transit time, energy expenditure, and vessel utilisation.

Research questions 5, 6, and 7 on exploring the digital twin's capacity to effectively and accurately represent real-world shipping conditions and formulating experiments were directly supported by the review of digital twins as simulation tools for building resilience. It was highlighted that digital twins are effective tools for modelling disruptions, identifying bottlenecks, and testing or identifying resilience strategies based on historical data or in real-time scenarios. These skills are put to the test in Chapter 6, which focuses on computer modelling and validation. With respect to resilience, the literature review argued resilience as being both recovery, referring to engineering resilience, and adaptability, referring to ecological resilience, highlighting strategies like redundancy, adaptive scheduling, and cross-agency collaboration (Holling, 1973; Wang & Yuen, 2022). These concepts and strategies relate to research question 8 by expanding on resilience techniques relevant to the aim of the study in enhancing operational efficiency in the Twente corridor; therefore, they reappear in the final chapter of the study to gain insight from the experiment results.

To conclude, the literature highlighted the problems of climate-induced disturbances on inland waterways, emphasising the role of simulating using digital twins for building resilience. A gap in the literature was identified, namely applying a digital twin simulation tool to the Twente Corridor and using KPIs to evaluate shipping scenarios under extreme water conditions. Therefore, the results of the study provided valuable guidelines for logistics stakeholders for the purpose of enhancing operational processes with resilience strategies to extend the use of inland shipping no matter the water conditions.

4 “Real world” Problem Analysis

In this chapter of the report is a full description of the operations in the Twente corridor, giving a specific and extensive response to the first research question that sought to discover the current practices of inland shipping in the Twente corridor. After a breakdown of the corridor’s environmental system, section 4.1 explains the shipping process for container goods, section 4.2 details the shipping process for dry bulk goods, then section 4.3 goes over the displacement series that affects management decisions when the Twente region is threatened by low water levels, and finally section 4.4 explains the most important management decisions that were considered in the research study.

4.1 Twente Canals and Environmental Conditions

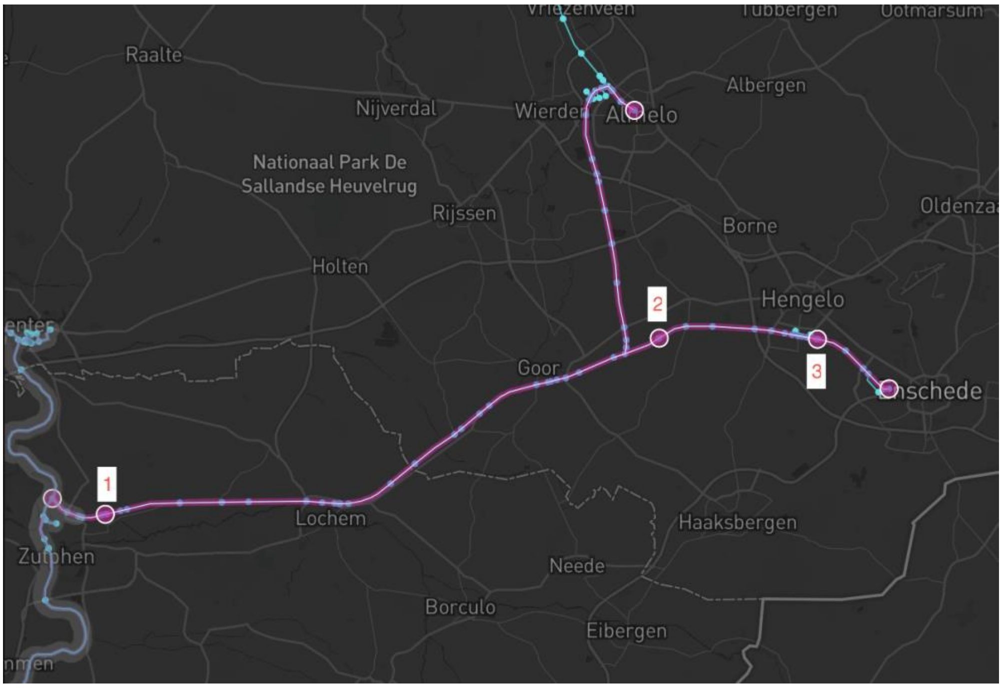


Figure 3 - Map of the Twente Canals

The canals in Twente are important to inland shipping in the Twente region, as well as water treatment and industry, seasonal water demand from the agricultural sector, water quality, and aquatic ecology, garnering an average demand for water of 15 m^3/s. By way of the lock and pump complexes at Eefde(1), Delden(2), and Hengelo(3), water from the IJssel is exchanged with the canals of Twente, the main system of the region. Water from the IJssel is pumped up to the next canal pound at each complex. Water can be delivered via this route to areas of Twente, the Gelderland portion of the Achterhoek, southwest Overijssel, and eventually, even Drenthe, thanks to the regional network. In order to maintain water levels and make up for losses from lock operation, leakage, evaporation, and influent seepage due to insufficient water supply from the canal through the streams that feed it (the Dinkel, Regge, Berkel, and Schipbeek), water from the IJssel is typically channelled in the summer period. A lack of water in certain areas of Overijssel, Gelderland, and Drenthe makes this necessary (Water Management in the Netherlands, the Kreekraksluizen in Schelde-Rijnkanaal, n.d.). It should be noted that the water in a canal can be managed more easily than a river, making it possible to maintain the standard water level of 10 meters NAP with $\pm 10\ cm$ above and below. This is done by storing water in the occasion that a drought ensues and once there is lower discharge flowing from the IJssel causing the water level in the canal to go below average, the stored water is released to maintain the water level requirements.

Figure 4 - Distribution of water through the branches of the Rhine, (Water Management in the Netherlands the Kreekraksluizen in Schelde-rijnkanaal, n.d.)

An important parameter to consider is the discharge rate of the Rhine River. As was mentioned above that the IJssel affects the water levels in the Twente canals, it should be noted that the main source of the water discharged by the IJssel comes from the river Rhine. The Rhine makes its way into the Netherlands at Lobith, and then downstream it splits into the Waal river, taking about two thirds of the water flow, and the Pannerdensch Kanaal, taking the remaining one third of water flow, subsequently splitting the Rhine east of Arnhem where the IJssel diverts a third of the total flow and departs from the Lower Rhine/Lek at the IJsselKop (Water Management in the Netherlands, the Kreekraksluizen in Schelde-Rijnkanaal, n.d.). A component of the water management system of the Dutch waterways is the use of barrages such as the dam at Driel, which, when closed due to low water, ensures that the water from the Rhine system flows as long as possible with a flow rate of 285 m^3/s via the IJssel to the IJsselmeer, leaving at least 30 m^3/s of flow rate left for the Lower Rhine. Whatever remains flows into the Waal river in the direction of the sea, serving as a barrier to prevent seawater incursion (Water Management in the Netherlands, the Kreekraksluizen in Schelde-Rijnkanaal, n.d.). This distribution between the three rivers allows for a reasonable water depth for navigation even during the dry seasons. In the case of a harsher dry season, when the flow rate at Lobith drops below 1300 m^3/s the IJssel will receive less than the usual 285 m^3/s (Water Management in the Netherlands, the Kreekraksluizen in Schelde-Rijnkanaal, n.d.). Contrarily, when the Rhine experiences a flow rate of more than 2400 m^3/s the dam at Driel, Amerongen, and Hagestein are fully opened, and the discharge via the IJssel will rise above the standard 285 m^3/s.

4.2 Containers

The order of events for container shipments in inland waterways is as follows: An order comes into the port of Rotterdam on a container sea vessel. Two or three inland waterway ships are sent by the inland terminal service provider to pick up the containers that have arrived. The number of vessels dispatched depends on the total TEUs of the freight. The logistics manager from the terminal keeps in contact with the operator of the ship to remain aware of the waiting times at the port in Rotterdam and account for any delays that could be incurred along the corridor. Once the containers are loaded into the ship, the operator confirms departure with the manager and then proceeds to make their way to the destination terminal in Twente. The fleet used for inland container transportation is all classified as 110m x 11,45m class Va ships. The process flow diagram below summarises the process defined.

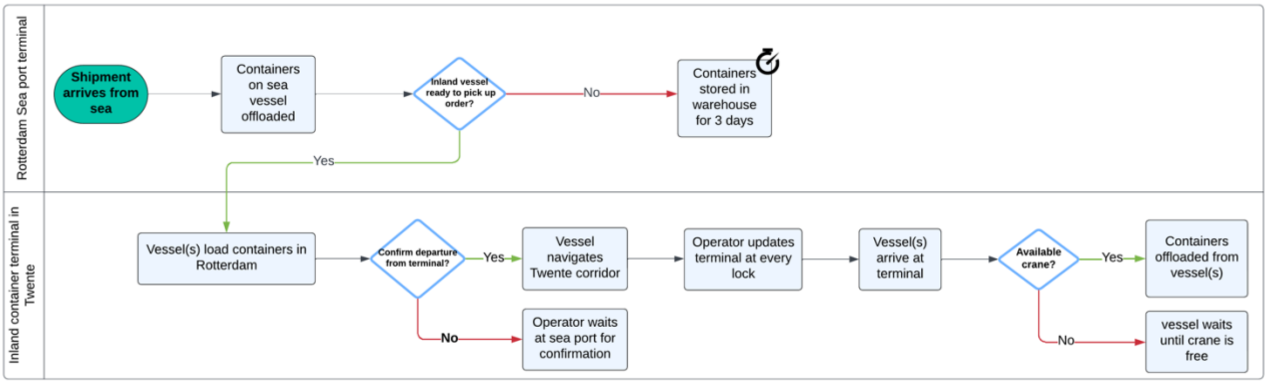


Figure 5 - Container shipment process flow

4.3 Dry Bulk

A case study of an animal feed company is used to analyse the inland shipping performance of dry bulk goods. The animal feed company partners with a logistics service provider whose responsibility is to provide transportation for the grain that arrives at the port of Rotterdam from sea vessels. The grain cannot remain in the warehouses at the port for no more than three days; therefore, the logistics service provider requires detailed knowledge of how much grain the feed company ordered and especially the water levels of the waterway during low water periods to ensure navigability. Since predicting water levels in the Netherlands is difficult due to fluctuating riverbeds, planning can be challenging. The logistics provider currently uses 110-meter class Va ships. To ensure precise logistics, the feed company informs the logistics provider of their tonnage requirements a week in advance, allowing for the collection of an exact amount of grain required by the feed company's factories taken from the sea ports.

When water levels are low, ships reduce their load and increase the frequency of trips. However, when levels become too low, trucks are utilised for transportation. The amount of raw materials, which are typically low density but high volume, determines how many ships can be dispatched, with ships having varying capacities. In times of low water, the availability of ships can be limited, leading to longer lead times of up to 8 weeks compared to the usual 1-4 weeks. The feed company schedules production based on stock levels, and during periods of low water, they adjust by maximising stock positions to maintain supply chain efficiency, despite the increased lead times caused by shipping constraints. A ship transiting the corridor usually takes a maximum of 3 days.

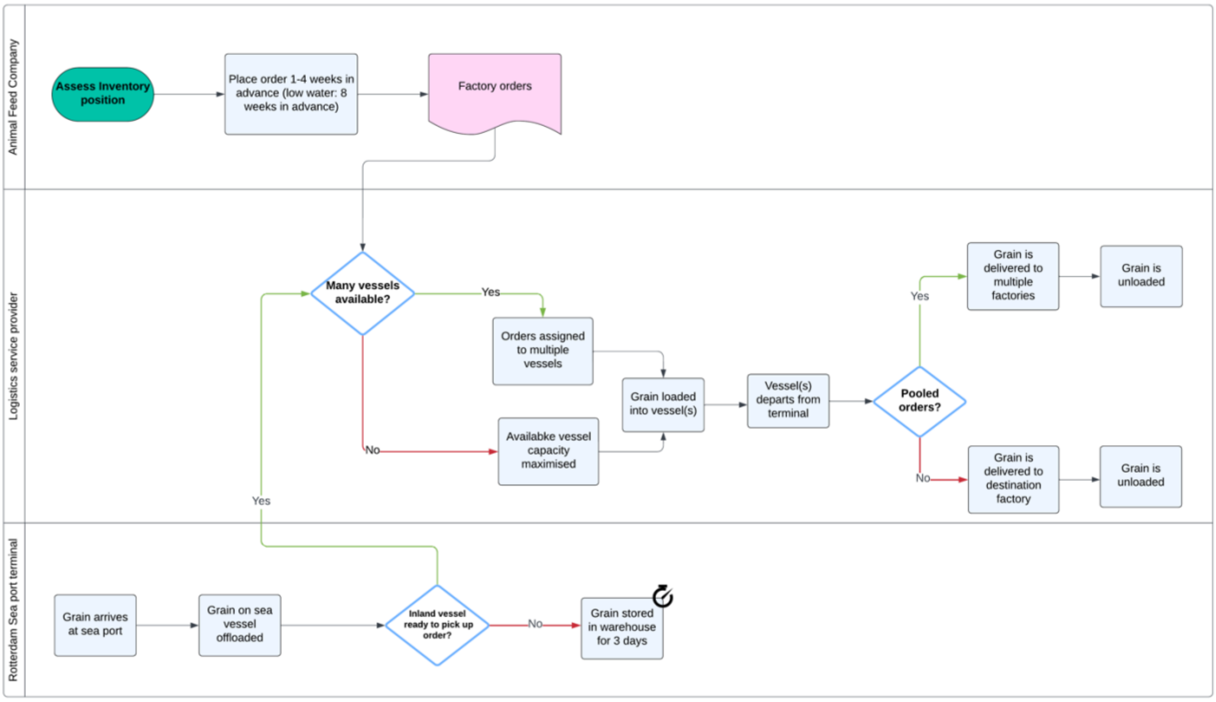


Figure 6 - Dry bulk shipment process flow

4.4 Displacement series

The displacement series, also known as the "Verdringingsreeks," is a hierarchy used during water scarcity. It provides a ranking for the distribution of water when a water shortage occurs. Kort & Bert (2003) state that a water shortage occurs when demand for water from various needs, social and ecological, surpasses supply of water of a standard fit for the various needs. In response to this dilemma, the displacement series was made to aid in choosing which interests should be given priority when the water manager, Rijkswaterstaat, can no longer meet all water needs. The series consists of four categories, with priority ranked in an ascending fashion. Category 1 constitutes safety and prevention of irreversible damage to waterways and their infrastructure. Category 2 constitutes utilities with respect to security and supply of drinking water and energy. Category 3 is for small-scale, high-quality use such as short-term irrigation of cash crops and the processing of industrial process water. Finally, category 4 constitutes other interests that may be of economic consideration but also for nature. Within category 4 are activities like agriculture, nature, industry, inland fishing, water recreation, shipping, and other interests other than the importance of security and supply.

This series is important to consider for inland shipping transportation, as this service resides in the lowest priority category within the displacement series. Shipping requires a certain water depth to ensure navigability; therefore, managers of companies that use inland shipping and operators require strategies that can make shipping still possible when the water level continues to drop. Therefore, management decisions for inland shipping become dependent on the displacement series. It should be noted that a province can establish a ranking within categories 3 and 4, meaning inland shipping can still be highly prioritised by the province so long as there is enough water to prevent damage to the waterways, to have security and supply of utilities, and to ensure small-scale, high-quality use of the water.

4.5 Management Decisions

When there is less water to navigate the inland waterways or too much water in the waterways, managers of inland shipping services need to decide on the best route for their ships to take to keep on schedule with their operations. The choice in routes will depend on the pickup point of the cargo and the final destination where the cargo is needed. Managers will also need to decide on how much cargo should be transported per trip and then decide on the size of the fleet, consisting of the number and class size of the ships that will be used to transport the cargo. All of these decisions depend on multiple factors that the managers need to be aware of. These factors include knowledge of the depth of water in the Rhine, ideally four weeks in advance, the waiting times at the port in Rotterdam for ships waiting to have their cargo loaded, the length of the queue at the locks in the Twente Corridor, particularly the lock at Eefde; subsequently, they will need to know the waiting times at the locks and if the bridge at Zutphen is open. Knowledge of these various factors will help the managers determine whether to give the ship operator the “go ahead” to make their way on the Twente corridor to the IJssel river or rather take a different route through Amsterdam. Once a barge enters the IJssel, there is no slowing down nor turning back, meaning that they have no other option but to proceed and enter the queues at the locks.

Research question two sought to identify current performance measures used in practice. Previous research explored in the systematic literature review has established that management decisions driven by assessing the performance of logistics planning currently use transit time, vessel utilisation, energy expenditure, and delay time as the main key performance indicators.

4.6 Conclusion

This chapter expounded on the Twente Corridor’s operational environment, concentrating on the canal system, logistics processes for container and dry bulk shipments, and the environmental consequences of fluctuating discharge rates on shipping operations. Regulated by water from the IJssel and assisted by locks, the Twente canals are vital not only for transportation but for regional needs as well. This chapter also touched on an important component in water management in the Netherlands, namely the displacement series, a system for determining and prioritising water allocation during shortages. It was highlighted that inland shipping is ranked in the lowest category; therefore, when water levels are low, inland shipping suffers challenges, thus requiring strategies that are adaptive for maintaining operations. Additionally, multiple factors, such as discharge rates, lock waiting times, and routing, need to be considered by managers of inland shipping services to make fleet movements optimal and efficient. Ultimately, the analysis in this chapter informs the knowledge questions explicitly by explaining current inland shipping practices, defining management challenges, and preparing the role of the digital twin in running simulations under various water conditions.

5 Conceptual Modelling

A conceptual model of the corridor was made by answering the third research question, which sought to identify the key concepts and objects that interact with the shipping vessels to create an abstraction of the real-world shipping process. A UML class diagram made on the platform Lucidchart was used to create the conceptual model. UML stands for united modelling language, and a class diagram is a type of UML diagram that is a graphical notation used to construct and visualise object-orientated systems. The following chapter begins with section 5.1 that covers the main concepts of the corridor in the form of the conceptual model, then sections 5.2 and 5.3 list and describe all the input and output variables found in the digital twin model, and the chapter concludes with section 5.4 that goes over the required data for the simulation experiments.

5.1 Main Concepts and Processes

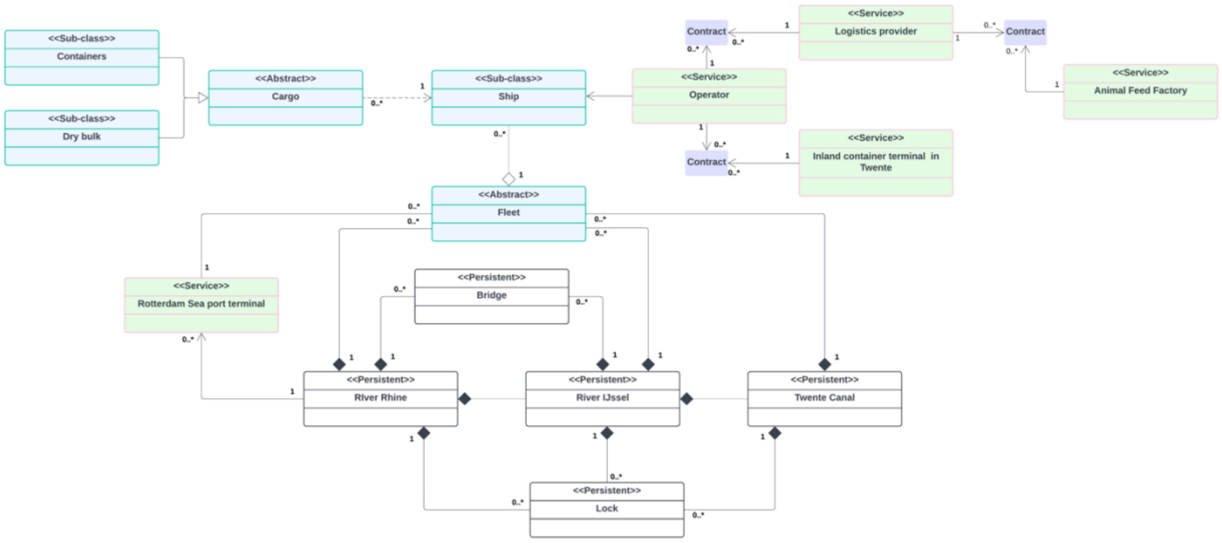


Figure 7 - Conceptual model of the Twente corridor

The conceptual model represents the physical system of the Twente Corridor in the context of the case studies being used in this research study. Figure 4 details the main concepts and objects of the corridor and the arrows between them represent their relationships. The concepts also have stereotypes enclosed in guillemets (<< >>), which are labels you can apply in UML above the element they modify. The stereotypes indicate that a UML element has a specific role or behaviour or belongs to a certain category. Table 1 gives a detailed breakdown of what the stereotypes mean and acts as a key to understanding the conceptual model. The stereotypes indicate that a UML element has a specific role or behaviour or belongs to a certain category. Table 1 gives a detailed breakdown of what the stereotypes mean and acts as a key to understanding the conceptual model. Furthermore, the concepts are grouped by colour, with the blue representing the objects that are involved with the shipping process, green representing the stakeholders of the shipping process, and white representing the immovable infrastructure that facilitates the shipping process.

Table 1 - UML Conceptual Model description

Category	Class	Role
Abstract	Cargo Fleet	A class that cannot be instantiated directly, thus it must be sub-classed
Sub-class	Containers Dry Bulk Ship	A class that inherits its properties from the parent class
Services	Animal Feed Company Inland container terminal in Twente Operator Rotterdam Sea port terminal	This class provides a specific service or operation within a system
Persistent	Bridge Lock River Rhine River Ijssel Twente canal	A class whose objects are persistently stored and are immutable

Locks have a composition relationship with the Rhine, the IJssel, and the Twente canal, meaning they cannot exist if both the rivers and canals no longer exist. The bridges have the same kind of relationship with the Rhine and the IJssel. The fleet also cannot traverse waterways if the waters themselves do not exist. The seaport terminal in Rotterdam and the fleet share a bi-directional relationship that is represented by a solid line. This indicates that an instance of one class is connected to the instance of another class. Inland fleets require sea port terminals as a contact point to pick up cargo that needs to be transported inland, and sea port terminals are made to manage the logistics processes of cargo that arrives from sea transits that are inland bound. Another important relationship is the dependent relationship that cargo has on the ship because the cargo requires a mode of transportation for it to be moved from one place to another. Furthermore, the ship requires an operator, and their relationship is a directed association, meaning that an operator is specifically associated with a ship. Similarly, ship operators have specific contracts with logistics service providers who handle the transportation of the dry bulk cargo for the animal feed company and the inland conatiner terminal. The following sections of this chapter detail the input and variables that constitute the main processes of the Twente-Rotterdam corridor.

5.2 Input Variables

For the digital model of the waterway system to digitally imitate the real-world system, input variables are used as system parameters that affect the system's performance. Input variables allow us to understand how a system behaves because their values can be changed, and in doing so, the output values also change. We seek to identify patterns in the way the variables interact and understand what this could mean for the waterway system. Table 1 details the input variables that can be manipulated during experiment simulations while using the digital twin model. They are described in the table in the same way that they are found in the model. These inputs in the model allow for the various concepts and objects depicted in the conceptual model to interact with one another to create a digital shipping process. In the following chapter is a thorough explanation of how these key variables interact in the digital twin model to create a simulation of a shipping process.

Input Variable	Variable Type	Description
Cargo type	Qualitative	Choice of cargo type between container or dry bulk
Waypoints	Qualitative	Operator's route of travel from start site to end site
Cargo load	Numerical	Cargo tonnage or TEUs to transport
Loading rate	Numerical	The number of tonnes or TEUs loaded into the ship per hour
Loading rate variation	Numerical	Error margin for the number of tonnes or TEUs loaded into the ship per hour
Fleet	Qualitative	Vessel class(es)
Fleet number	Numerical	Number of vessels in the entire fleet for the trip
Velocity	Numerical	Vessel velocity [m/s]
Discharge	Numerical	Water flow rate of the river(s) $[m^3/s]$
Under keel clearance	Numerical	The water depth between the bottom of the vessel and the riverbed
Vertical clearance	Numerical	Distance above the air draft that allows the vessel to pass safely under a bridge
Cargo capacity	Numerical	The maximum load that can be carried by the vessel while having a navigable draft/clearance

Table 2 - Input variables used in the digital twin model

5.3 Output Variables

The system's performance is indicated by the output variables of the digital twin model. The study's fourth research question, which sought to identify key performance indicators relevant to performance-based resilience, was already partially addressed in the literature review found in chapter 3. Table 2 describes the relevant key performance indicators in the form in which they are found in the digital twin model.

Output Variable	Variable Type	Description
Trip duration	Numerical	The length of time in hours of the trip
Sailing time	Numerical	Length of time in hours of the vessel’s transit time on the corridor
Loading time	Numerical	Length of time in hours of the cargo loading and unloading process
Trips	Numerical	The number of trips the vessel(s) needed to transport the entire cargo load
Energy by distance	Numerical	The energy consumed by the fleet over the distance traveled in kWh/km

Table 3 - Output variables of the digital twin model used as the key performance indicators of the system

Another key performance indicator not directly found in the digital twin model but was derived from the output variables of the model is found in table 3. This key performance indicator was also identified in the literature review.

Derived Output Variable	Variable Type	Description
Vessel utilization	Numerical	Percentage of the vessel’s usage capacity found by comparing the maximum load against actual load

Table 4 - Additional key performance indicators

5.4 Required Data

The required data was the specific data inputs needed to initialise and run the digital twin model, making sure that the simulations accurately represented the operational conditions of the inland waterway system under climate stress. This data was utilised to simulate port and terminal logistics operations, ship movements, and environmental factors. Operational data was retrieved in the form of interviews and emails with the companies that were used as case studies for this research. Environmental and hydrological data was retrieved from a research study by Vinke et al. (2024) that analysed the effects that discharge extremes have had on inalnd shipping within the Rhine corridor, spanning over ten years.

Operational data refers to the order details of the cargo, vessel characteristics, and cargo handling rates. The order details comprise the exact location of the seaport terminal and inland shipping terminals for order pick-up and order delivery of both dry bulk and container shipments. Fleet characteristics include the vessel class and dimensions, the number of vessels, cargo capacity of each vessel type, velocity, and draft clearance. The cargo handling rates are the loading rates and loading rate variations of dry bulk and of container cargo at the sea port terminal and at the inland shipping terminal. Environmental and hydrological data refers to the river’s discharge flow rate in cubic meters per second.

5.5 Conclusion

A conceptual model for simulating the corridor’s inland shipping operations was outlined in this chapter. Key entities and interactions within the system were addressed in response to the third research question. A UML class diagram was used to visualise the conceptual framework, representing the physical and logistical structure of the corridor and highlighting important relationships between fleet, cargo, waterways, and infrastructure. The chapter continued further to list and define input variables key to the simulating real-world conditions in the digital twin, as well as outline the output variables that would function as performance indicators. Lastly, the required data for the simulations consisted of an integration of environmental and operational data provided by literature and from interviews over the case studies.

6 Computer Modelling and Validation

The chapter proceeds with section 6.1 that details the settings used for the simulation experiments, then proceeds to section 6.2 that explains the data used in the simulation experiments, and wraps up with section 6.3 that discusses the validity and realiability of measurement.

6.1 Digital twin model

The fifth research question asked how the model uses key variables to represent the effects of low and high water levels on the navigability of different ships along the Twente Corridor. Figure 8 illustrates how the model's core methods use specific input variables at each step of the model to output an important feature of the shipping process and environment. By setting values for the cargo type, the route in terms of the waypoints, the cargo load, the laoding rates, and loading rate variations of the start and end sites, the digital twin model instantiates an operator who creates a plan for the shipping process. The type of fleet and the number of vessels within the fleet, as well as their velocity, are also input variables that can be set by the model's user and are part of the operator's task within the model. The user can create an environmental condition for the shipping simulation by changing the discharge variable of the river Rhine or the Meuse if needed, and this in turn results in the model calculating the water depth all throughout the chosen route. Once the environmental condition for shipping is set, the vessel's clearance settings must be adjusted by the model's user to make sure the ship can navigate the route in the waterway; otherwise, the model will not be able to run the simulation. To meet the clearance level, the fleet's cargo capacity should be adjusted appropriately. Finally, once all the input parameters are set, the simulation can be run and an animation of the shipment can be observed on the topological map of the model's interface.

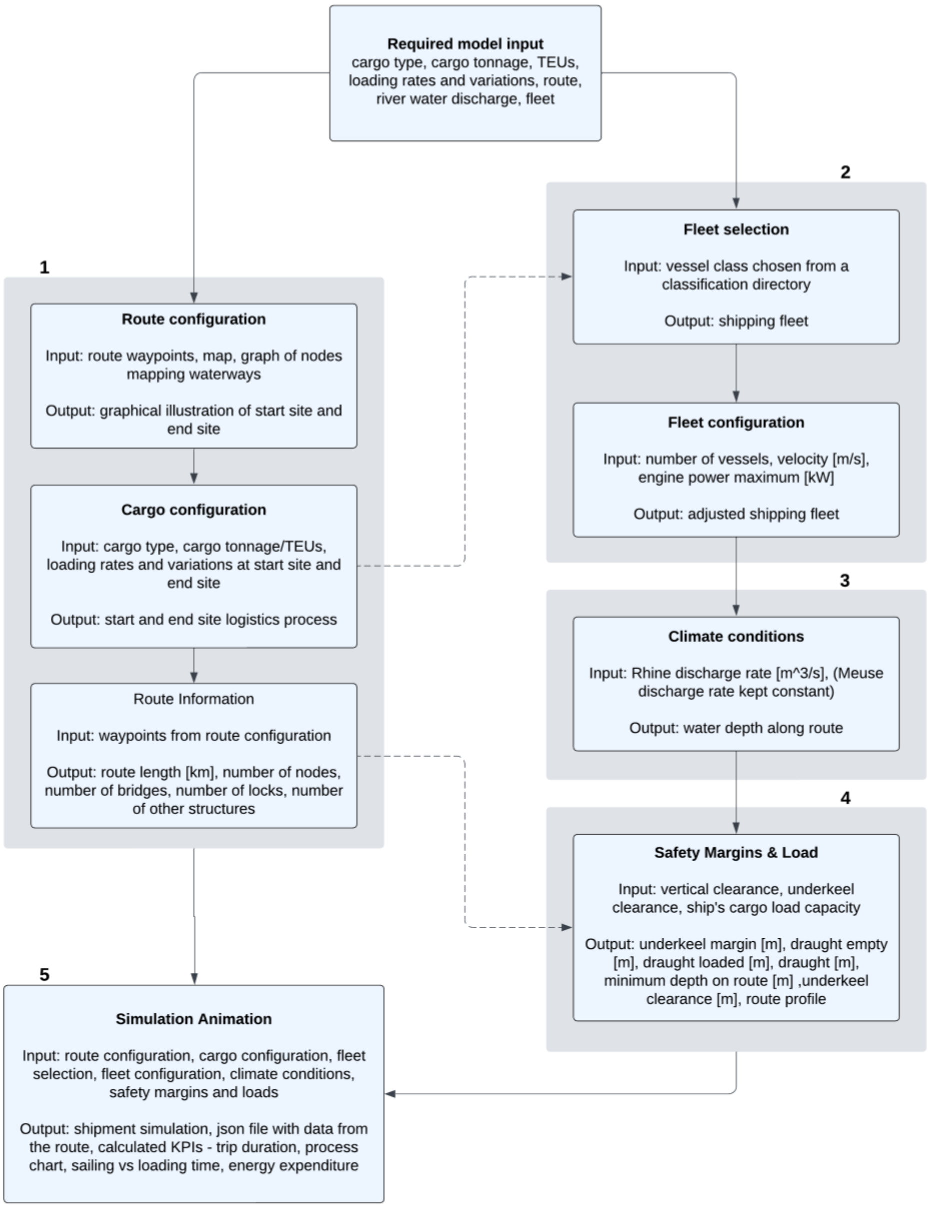


Figure 8 - Modelling flow diagram

6.2 Simulation settings

The simulation settings are the input parameters that will remain the same throughout the experiments. These settings are detailed in Table 4, and they remain the same for any environmental condition being tested. It should be noted that the inland shipping terminals being used for the simulations are both located in Almelo. Almelo is the only destination in common in the historical order data of both case studies; therefore, it made it easier to compare the results given the route would remain the same for both dry bulk cargo and containers.

Cargo Type	Dry Bulk	Departure waypoint – 8866119: Rotterdam Europoort, EBS EP II, Beneluxhaven	Loading rate – 300 tonnes/hr Loading rate Variation – 0 tonnes per hour
		Destination waypoint – Berth 270: ForFarmers Almelo	Loading rate – 150 tonnes/hr Loading rate variation – 0 tonnes/hr
	Container	Departure waypoint – 8863919: Rhenus Deep Sea Terminal	Loading rate – 22.2 TEU Loading rate variation – 2.4 TEU
		Destination waypoint – B51471_A: CTT Almelo	Loading rate – 22.2 TEU Loading rate variation – 2.4 TEU
Ship Velocity	13 m/s		
Vertical Clearance	Refer to Appendix B		
Under keel Clearance	Refer to Appendix B		

Table 5 - Settings for simulation experiments

6.3 Simulation Experiments

The resulting experiments focused on analysing the following known industry practices:
Under low water levels:

- Barges transporting containers, 2 or 3 levels, can traverse through low water.
- Barges transporting dry bulk goods cannot traverse through low water.

Under high water levels:

- Barges carrying containers, 2 or 3 levels, cannot traverse through high water.
- Barges carrying dry bulk goods can traverse through high water.

Additionally, Vinke et al. (2024) identified in their data analysis three discharge ranges from the Rhine, namely low, medium, and high, and quantified these levels in three discharge bins. This informed the decision to use in the experiments a low water discharge of 1000 m^3/s, a normal water discharge of 2000 m^3/s, and a high water discharge of 4500 m^3/s. The discharge bins found in literature were:

- Low discharge range: 700 – 1200 m^3/s
- Regular discharge range: 1200 – 4500 m^3/s
- High discharge range: 4500 – 8500 m^3/s

When running experiments, it was imperative to monitor the navigable depth of the vessels. As advised by the logistics service provider, water depth for agribulk (dry bulk) is typically between 2,50 – 2,80 m. This water depth range is the same for the inland shipping terminal provider, as they too advised that container ships require a depth of 2,50 - 2,80 m. When the water depth of the river or canal ranges between 2,20 – 2,50 m, some navigation issues begin to factor in. Navigation problems become particularly challenging for the larger fleets between a range of 1,20 – 1,30 m, however, older and smaller vessels can navigate water depths of 1,10 m. It has been observed that the lowest point of the IJssel is 1,40 m, and many ships cannot navigate through this point when the water discharge rates cause the river's water depth to go any lower than this value. The clearance values for the vessels used in the experiments can be found in Appendix B.

Fleet Description	Vessel Type	CEMT-Class	RWS-Class	Dimensions	Cargo capacity (tonne)	Cargo Capacity (TEU)
Kempenaar	Motorvessel	II	M2	55m x 6.6m	617	48
Rhine Herne Vessel	Motorvessel	IVa	M6	85m x 9.5m	1537	96
Large Rhine Vessel	Motorvessel	Va	M8	110m x 11.4m	3013	208
Ext. Large Rhine Vessel	Motorvessel	Va	M9	135m x 11.4m	3736	272
Rhinemax Vessel	Motorvessel	VIa	M12	135m x 17m	6082	434

Table 6 - Classification of vessels used for the experiments

Table 5 details the vessels that were chosen for the simulation experiments. These vessels are the only ones listed because the companies in the cases being used for this study currently use M8 motorvessels. Under low water conditions, the fleet adjustment strategy was implemented. To experiment with a small vessel, an M2 motorvessel was used, and to experiment with a midsized vessel, an M6 motorvessel was used. These smaller options were chosen to ensure navigability as well as to give stakeholders an idea of how these two ship sizes would fair under low water conditions. Under higher water levels, the current M8 vessel is used as a benchmark against other larger ships, namely M9 and M12 motorvessels, to analyse if fleet adjustment strategy would hold useful under flooding conditions where clearance under bridges is at the highest risk. The thought behind these larger vessel choices was that a larger vessel would make it possible for containers to carry more TEUs with only 2 levels of cargo.

Table 7 - Container input values for cargo to transport

Cargo Type	Cargo Load
Container	100 TEU
Container	200 TEU

Table 8 - Dry bulk input values for cargo to transport

Cargo Type	Cargo Load
Dry Bulk	1000 ton
Dry Bulk	2000 ton

In tables 6 and 7 are the cargo loads that were used in the experiments. These values were retrieved by aggregating the historical data in the form of orders handled by the inland shipping terminal for containers and the logistics provider for dry bulk. Additionally, two rounds of experiments were run, with the first round's purpose to be the control run and the second round to validate the reliability of the simulation results. The results of both rounds were identical in their outcomes with respect to trip duration, sailing and loading times, as well as energy expenditure. The only difference was the starting date and time of the simulation. This feature of the model was often random, choosing any arbitrary time and date to begin the shipping operations. The experiments yielded the following evaluation results:

1. *Container: Transit time*

Container shipments carrying 100 TEU have transit times that range between 16,9 hours (low water) and 24,9 hours (high water). For 200 TEU, transit times range between 17 hours and 24,9 hours. Under normal water levels, using both 100 TEU and 200 TEU has a transit time of approximately 20.01 hours. Evaluation of the data indicates that high water levels result in longer waiting times, particularly the larger the cargo load and vessel size become.

2. *Container: Loading time*

Assessment of loading time across different vessel types and water level conditions highlights that loading time ranges from 9 hours to approximately 18 hours. 100 TEUs take about 9 hours to be loaded into the vessels, no matter the size, meaning doubling the TEUs loaded also doubles the loading time.

3. *Container: Vessel utilisation*

The evaluation criteria ranges from 48% to 96% for normal water levels, from 52% to 83% for low water levels, and from 23% to 96% for high water levels. These values tell us that low water conditions lead to higher vessel utilisation due to using smaller vessels than those used under normal and high-water conditions. High water conditions make it easier to use larger vessels; however, this causes a sharp drop in vessel utilisation for this set of experiments. In the real world, it is more likely that more containers will be transported if there remains a large surplus in cargo load capacity. However, in these simulations, the purpose of using larger M9 and M12 vessels is to observe their effectiveness since it could be theoretically possible to transport the same volume of cargo by spreading the containers over a larger area, resulting in fewer container levels.

4. *Container: Number of trips*

The number of trips means the total amount of transits the entire cargo load needs to arrive at the destination location. Low-water conditions require a range of 2 to 5 trips depending on the amount of cargo load being transported, whereas normal and high-water conditions only require one trip to transport cargo. The heavier the load, the more vessels that are needed, therefore the higher the number of trips. A cause for this pattern is the use of the smaller M2 and M6 vessels that have a smaller load capacity compared to the larger M8, M9, and M12 vessels, which only require one vessel and thus one trip.

5. *Container: Energy efficiency*

Energy consumption under normal water levels remains at 0.0442 kWh/km, whereas low water levels are ranging from 0.0332 to 0.0437 kWh/km. Smaller vessels require multiple vessels within the same fleet in order to ship the same load as larger vessels. This leads to the fact that the fleet of smaller vessels will expend more energy due to needing multiple ships to transport the same load. Within this range, it can already be observed that energy consumption increases as the size of the vessel increases; additionally, for low water conditions, an increase in cargo load also increases energy consumption, however, it is most efficient per TEU to transport higher loads although it requires more ships. Significantly more energy is consumed under high water conditions, with energy consumption ranging from 0.0386 kWh/km to 0.0612 kWh/km. M8 vessels under high water are the most energy efficient, particularly when vessel utilisation is as high as possible.

Containers										
Water level	Cargo load (TEU)	Vessel Class	Nr. of Vessels	Trip duration (hrs)	Sailing time (transit time in hrs)	Loading time (hrs)	Nr. of Trips	Energy by distance per vessel (kWh/km)	Energy by distance per TEU (kWh/km/TEU)	Vessel Utilization (%)
Normal (2000 m3/s)	100	M8	1	29,01	20,01	9	1	0,0442	0,000442	48,1
	200	M8	1	38,02	20,005	18,018	1	0,0442	0,000221	96,2
Low (1000 m3/s)	100	M2	3	26,008	16,999	9,008	3	0,0332	0,000332	69,4
		M6	2	27,207	18,198	9,009	2	0,0412	0,000412	52,08
	200	M2	5	35,017	17	18,017	5	0,0387	0,0001935	83,33
		M6	3	36,216	18,198	18,018	3	0,0437	0,0002185	69,4
High (4500 m3/s)	100	M8	1	28,921	19,912	9,009	1	0,0386	0,000386	48,1
		M9	1	27,589	18,579	9,009	1	0,0454	0,000454	36,8
		M12	1	34,0003	24,991	9,009	1	0,0612	0,000612	23,04
	200	M8	1	37,929	19,912	18,018	1	0,039145	0,000195725	96,2
		M9	1	36,598	18,579	18,018	1	0,0455	0,0002275	73,53
		M12	1	43,009	24,991	18,018	1	0,0598	0,000299	46,08

Table 9 - Results of simulations from container shipments

6. *Dry bulk: Transit time*

Vessels transporting dry bulk goods had similar patterns to those transporting container goods. Transit times under normal water conditions range from 19.2 hours to 19.8 hours. The smaller M2 and M6 vessels under low water conditions have a slight decrease in transit time with a range from 16.7 hours to 18 hours, meaning smaller vessels are faster and save time even though they sometimes require multiple trips. Under high water conditions, larger ships like the M12 have the longest transit time of 24.7 hours. It is interesting to note that the slightly larger M9 vessel has a shorter transit time of 18.3 hours compared to the 19.7 hours of the M8 vessel that is usually used in the corridor. Under high water conditions, the M9 is most efficient.

7. *Dry bulk: Loading time*

Loading times range from 6.2 hours (low water) to 20 hours (high water for larger vessels). The results show that the smaller the vessel, the faster the loading time, no matter low or high-water conditions. This could be attributed to the fact that the volume of smaller vessels fills up faster than that of larger vessels. M2 vessels had loading times of 6.1 hours and 8.7 hours for 1000 tonnes and 2000 tonnes, respectively; M6 vessels had loading times of 10 hours and 14.9 hours, respectively; and M8 ships had loading times that ranged from 10 hours to 17.4 hours. These vessels sometimes had multiple vessels deployed at a time, therefore being another reason behind the increase in loading times other than the cargo load increasing for these ships. For the M9 and M12 ships, when the load doubled, so did the loading time.

8. Dry bulk: Vessel utilisation

Similar to the container simulations, low water conditions result in higher vessel utilisation due to the smaller M2 and M6 vessels having a lower maximum cargo capacity, making it easier to max out their capacity. Vessel utilisation values range from 16.4% (high water) to 81% (low water). M8 vessels under normal and high-water level conditions have either 33.2% or 53.1% vessel utilisation, meaning the higher water conditions limit the load capacity of the vessel due to the safety clearance. The M9 and M12 vessels can carry more load and are only limited by the order size used in the simulations to mimic the real-world orders.

9. Dry bulk: Number of trips

To maintain throughput, it is necessary to double the number of trips under low water levels when using M2 and M6 vessels. It is interesting to note that for dry bulk, safety clearance limits the cargo load capacity of M8 vessels to 1600 tonnes as indicated in Appendix B; therefore, the number of trips for these vessels when transporting 2000 tonnes required 2 vessels and not just one, as would be expected if the max capacity of the ship is 3013 tonnes.

10. Dry bulk: Energy efficiency

Energy consumption ranges from 0.333 kWh/km to 0.0549 kWh/km. Although the highest value for dry bulk shipments consumed less energy than the highest value for container shipments, the energy consumption trend remains the same. Significantly more energy is burnt during high water conditions, particularly by the M12 vessel, however, energy consumption per tonne decreases as load increases, therefore it is more efficient to utilise more of the vessel's capacity. Once again, the smaller M2 and M6 vessels require more trips to transport the same amount of load as the larger vessels, therefore they burn more energy than the single vessle fleets. Similarly, the higher the load, the less energy is consumed per metric tonne although multiple vessels belong to a single fleet. The most efficient larger vessels under high water conditions are the M8 and M9 vessels, with energy consumption values ranging from 0.042 kWh/km to 0.0455 kWh/km, particularly the M8 whose energy per metric tonne is the lowest.

Dry Bulk										
Water level	Cargo load (Tonne)	Vessel Class	Nr. of vessels	Trip duration (hrs)	Sailing time (transit time in hrs)	Loading time (hrs)	Nr. of Trips	Energy by distance (kWh/km)	Energy by distance per tonne (kWh/km/tonne)	Vessel Utilization (%)
Normal (2000 m3/s)	1000	M8	1	29,8	19,8003	10	1	0,0442	0,0000442	33,2
	2000	M8	2	36,634	19,233	17,401	2	0,0442	0,0000221	53,1
Low (1000 m3/s)	1000	M2	2	22,977	16,783	6,194	2	0,0333	0,0000333	81,04
		M6	1	28,007	18,007	10	1	0,0412	0,0000412	65,1
	2000	M2	4	25,46	16,783	8,677	4	0,0333	0,00001665	81,04
		M6	2	32,841	17,97	14,871	2	0,0435	0,00002175	65,1
High (4500 m3/s)	1000	M8	1	29,707	19,707	10	1	0,0428	0,0000428	33,2
		M9	1	28,369	18,369	10	1	0,043	0,000043	26,77
		M12	1	34,702	24,702	10	1	0,0558	0,0000558	16,4
	2000	M8	2	36,54	19,716	16,824	2	0,0424	0,0000212	53,1
		M9	1	38,369	18,369	20	1	0,0455	0,00002275	53,5
		M12	1	44,702	24,702	20	1	0,0549	0,00002745	32,9

Table 10 - Results of simulations of dry bulk shipments

6.4 Validity and Reliability in Measurement

Validity can be assessed in three ways, namely construct validity, internal validity, and external validity. Construct validity ensures that the simulation framework accurately represents the real-world processes it intends to simulate, therefore validating that the relevant variables, like discharge rates, fleet types, cargo loads, vessel speed, and loading rates, interact in accurate ways. The construct validity of the digital twin model was conducted by creating the conceptual model that the digital twin inputs and outputs are derived from. The comparison of the digital twin's model flow diagram and the conceptual model of the Twente indicated that the digital twin model accurately captures the dynamics of inland waterway transportation. This was evident by way of how the core concepts were operationalised by the simulation model; for example, in the diagram, discharge rates of the Rhine affect the Twente corridor. This is also evident in the simulation model when the set discharge rate determines the navigable depth of the corridor and thus the vessel clearance. Furthermore, the conceptual model and simulation model exhibit process flow alignment, aligning with real-world activities in the shipping process, such as the phases of engaging an operator, who then plans the route and then loads cargo onto the vessel, tranits the corridor, and unloads the cargo upon arrival at the destination terminal. Ultimately, the transparent nature of the flow diagram reinforces confidence in the construct validity of the model as it allows for a visual evaluation and verification of the model's logic, relationships between variables, concept interactions, and thus consistency with real-world expectations.

Internal validity addresses thorough testing of the simulations from the model to make sure that the observed changes in the results are comparable with the results of the real-world system. This form of validation is referred to by Robinson (2014) as black-box validation. The overall behaviour of the model is what is considered, meaning if confidence is to be put in the model, then the outputs of the model should be sufficiently the same as the real-world system when the model is run under the same inputs as the real-world system. It was advised in interviews held with managers of the inland container terminal that ships departing from the port in Rotterdam typically have a transit time of approximately 18 hours without stipulated rest time. The average transit time under low water levels was 16 hours, the average transit time under high water levels was 21 hours, and the average transit time under normal water levels was 19 hours. These average transit times show that the transit times under all conditions closely align with the historical shipping data, particularly for the normal water level conditions.

Finally, for external validity, cautious measure should be taken to make certain that the simulation conditions, especially extreme water levels, are representative of the water levels likely to happen in the the real-world. Taking this caution of capturing the crucial aspects of the corridor's operational environment will give the ability to generalize findings from the simulation to real-world situations along the Twente Corridor. To do this form of validation, water levels over the past ten years, focusing on periods that had low or high water as advised in a study by Vinke et al. (2024), were analysed using the waterinfo website hosted by the Rijkswaterstaat. On this site historical data of water discharge rates can be accessed by choosing a time period. The site also has a legend that classifies the various statuses of the water discharge along Dutch waterways, aiding in identifying the relevant data to cross reference the information found in literature. The outcome was that the discharge rates of the Rhine found in literature indeed were aligned with historical data of discharge rates of the Rhine in reality, therefore validating the environmental conditions of the simulations in this study.

The reliability of measurement in the modelling and experimental phases of this study refers to the consistency of the model's results when the same input variables are implemented. To test this, repeated runs of the simulation using the same conditions verified that the model produced stable and consistent results. In addition to this, the input-output mapping illustrated by the modelling flow diagram was essential for ensuring that the simulation correctly transalated input variables, like fleet type, cargo load, and cargo loading rate, into output KPIs like duration time of the transit, as well as loading duration and unloading duration, all without significant errors or variability arising.

6.5 Conclusion

The digital twin's modelling framework was outlined in this chapter, showing its capacity to simulate the Twente corridor's inland shipping operations under varying environmental and operational conditions. The model's simulation process, particularly which input variables result in specific output variables within a certain step of the simulation model, was visualised using a process flow diagram, therefore addressing the fifth research question. Simulation settings, referring to the model's configurations that remain constant, and variable values derived from industry practices were defined to test operational feasibility under climate stress, therefore responding to the sixth research question that was made to guide the formulation of experiments. Furthermore, the validation measures, such as construct, internal, and external validation, were taken to ensure the model's accuracy. This was done alongside reliability assessments, which were conducted by means of conducting multiple runs of the same experiments. The model’s simulated transit times under various water conditions exhibited close alignment with real-world data, confirming the model’s efficacy, supporting its use for evaluating shipping scenarios under fluctuating water levels to create resilience strategies, and answering the seventh research question about the accuracy of the model.

7 Conclusion & Understanding

To conclude the report, the results of the experiments are analysed in table form to create evaluation criteria and then suggest an implementation plan in response to the final sub-research question. This chapter details in Section 7.1 the results, which are recorded in Tables 9 and 10, in Section 7.2 the contribution of this study, which is an implementation plan of the relevant shipping strategies; in Section 7.3, which discusses the limitations of using the digital twin model for a simulation study; and finally, Section 7.4 suggests future work for research and development to further knowledge in the field of resilience in waterway transportation.

7.1 Discussion

The main objective of the study was to identify the most effective shipping strategies for inland shipping performance when simulating inland waterway transportation under climate stress in order to increase resilience in the Twente corridor. Addressing the main research question, which sought to understand how simulation could be used to determine the impact of weather extremes within the Twente corridor, resulted in discovering that loading times are unaffected by water level fluctuations. Additionally, larger ships are slower than smaller ships irrespective of the water level, even when they could be transporting the same volume of cargo. Although smaller ships are navigable when faced with low water conditions, a big impact of the low water level is the need for multiple ships, therefore multiple trips, to transport the same load as a bigger ship.

Presented in this study is a novel approach to analysing the impact of climate-induced stress on inland waterway logistics, specifically on the Twente corridor. This approach also allows for the analysis of resilience within this corridor. Prior research has only focused on exploring resilience in major European corridors such as the Rhine corridor; the focus on the Twente corridor in this study addresses an important gap and does so by including localised environmental and operational factors unique to the Twente region. The use of a digital twin model to simulate the effects of water level extremes on transit times, operational efficiency, and navigability, all the while integrating dynamic environmental variables into its simulation capabilities, offers a novel contribution as the use of digital twins in inland waterway transportation is still in the early stages of research. This opens the possibility for real-time monitoring of waterway logistics processes and predictive and prescriptive insights that can enhance informed decision-making that can be applied immediately by managers of inland shipping services. In addition, the simulation framework from this study aids in testing resilience strategies such as fleet adjustments under varying environmental conditions. The simulation framework is operationally relevant as it incorporates performance-based resilience metrics, a feature only recently gaining traction in the literature of the years. Furthermore, the conceptual model is a solid model that validates the relationships between key variables, making sure the digital twin accurately depicts the interactions within the waterway logistics system, which are more complex. Ultimately, these elements highlight the framework as a novel tool in the field of inland water resilience modelling, implicating both practical application and research. This research emphasizes the importance of simulation-based planning in addressing climate stress in inland logistics corridors.

Although the strategies that are mentioned in this study cannot be tested directly in the real-world system to evaluate the effectiveness of the simulation experiments, an implementation plan is proposed to the inland shipping service providers and users. Based on the above results, the first strategy is to prioritise high-utilisation of vessels under both low and high water levels. Although the number of vessels needed increases, especially under low water conditions, this reduces the energy consumption per metric tonne or per TEU transported if the vessels within a fleet are nearing maximum vessel utilisation. The second strategy would be to implement dynamic vessel planning that requires monitoring water levels periodically to prepare beforehand a fleet of vessels on such as M2, M6 under low water extremes, or M9 vessels during high water conditions. Vessel speeds can also be adjusted along the route based on the water conditions, such as slower speeds during high water levels, to reduce excessive energy consumption without drastically increasing the transit time. Another strategy could be to prioritise M6 vessels under low water conditions to reduce the number of vessels required to transport the same volume of cargo if it is infeasible to deploy as many as five M2 vessels for a single shipment. Under high water conditions, it could be beneficial to prioritise the use of M9 vessels rather than the current M8 vessels being used to reduce the number of trips back and forth from the seaport to the inland terminal as load increases, as well as to have bridge clearance with more ease.

7.2 Limitations

As with any model, the digital twin comes with its limitations. Firstly, simulating shipments as close to reality as possible is not feasible using the digital twin due to the problem that the user cannot model multiple orders on a single ship, e.g., an M8 vessel filled with 1500 tonnes worth of dry bulk for both factory locations in Lochem and Almelo, whose orders are 1000 tonnes and 500 tonnes, respectively. In many cases, clients of the logistics service provider pool their orders in order to decrease the cost of transportation. Secondly, when configuring the cargo load, the user can only adjust the load by steps of 1000 tonnes or 100 TEU; therefore, the simulated cargo load cannot be as precise as the real-world load. Thirdly, the loading rates and loading rate variations for both dry bulk and especially container cargo had to be approximated as close as possible to the values advised by industry professionals, once again, due to the step count of the numerical sliding component in the digital twin. Additionally, another unfortunate limitation of the study was that the sample sizes of the real-world data and the model data are not comparable; therefore, it was enough to be advised of the general transit time of a vessel on the Rotterdam-Twente corridor by industry experts. Finally, although the logistics service provider and the inland container terminal use 110-meter ships, these M8 vessels could not be used under the environmental condition of low water levels. The model would crash whenever this experiment was attempted, probably due to the ship's depth clearance not being enough across the entire route.

7.3 Future work

To conclude, further research and development can be explored by extending the capabilities of the digital twin model. An example could be configuring the current model to include parallel loading processes that would allow for the shipment simulations to have improved loading processes that are closer to the real-world process rather than load the cargo into a vessel one after the other as is done in the model. The need for this improvement is that terminals such as the inland container terminal used as a case in this study have multiple cranes operating simultaneously. This streamlines their terminal operations, and therefore the model should incorporate this important feature. The model would have to be developed further by accessing the source code that is currently public on GitHub. Furthermore, this feature could be used to research the optimal number of cranes for loading operations. Another area of research would be to explore the effects of using priority scheduling within the Twente corridor when there are water level extremes. Priority scheduling can be used as a resilience-building strategy aimed at long-term adaptability if implemented in operational policies and practices at seaports and inland terminals. These could be allowing container vessels to leave the port before dry bulk vessels or prioritising vessels based on the volume of the cargo rather than the cargo type, and so on. This research can be conducted using the digital twin to simulate shipping scenarios and then apply a priority queuing model to the results. Furthermore, the model can also be improved to allow a user to model multiple cargo orders on a single ship. Currently this functionality is not available on the digital twin, although cargo pooling is indeed currently practiced by companies to minimise transportation costs. Research on this technique can explore how cargo pooling and inland shipping performance are affected by water level fluctuations and what this means for ships that need to pass through multiple stops to offload cargo. Finally, a considerable improvement to this research would be to simulate shipping scenarios for all thirty-two vessel types available in the digital twin model under discharge extremes. This would give a larger range of options when creating flexible planning, as well as create more knowledge on what ships are infeasible to use based on certain environmental conditions and which ships are more efficient to use than others under environmental stress.

8 References

Babiche. (2023, March 23). *Twentse bedrijven werken samen aan de Twente corridor.* Joint Corridor off Road. https://go-off-road.nl/twentse-bedrijven-werken-samen-aan-de-twente-corridor/

Busse, A., Gerlach, B., Lengeling, J. C., Poschmann, P., Werner, J., & Zarnitz, S. (2021). Towards Digital Twins of Multimodal Supply Chains. *Logistics*, *5*(2). https://doi.org/10.3390/logistics5020025

Central Commision for the navigation of the Rhine, 2020. Information fairway rhine. URL https://ccr-zkr.org/13020600-nl.html.

Chakravartty, A.: Scientific realism. In: Zalta E.N. (ed.) The Stanford Encyclopedia of Philosophy (Summer 2017 Edition). https://plato.stanford.edu/archives/sum2017/entries/scientific-realism/ (2017)

Cooper, D. R., & Schindler, P. (2014). Business research methods. Mcgraw-hill.

Deltares-Research. (n.d.). *GitHub - Deltares-research/digitaltwin-waterway: Code and notebooks for the Digital Twin Waterway*. GitHub. https://github.com/Deltares-research/digitaltwin-waterway

de Leeuw van Weenen, R., van der Geest, W., Kawabata, Y., van Berne, B., van Meijeren, J., & Kraan, M. (2019). *Impactschatting Risico Reverse Modal Shift Containervervoer In opdracht van de Topsector Logistiek*.

Desai, K. J., & Prock, J. (n.d.). *A SIMULATION STUDY OF OPERATIONAL PROCEDURES FOR INCREASING THE EFFICIENCY OF INLAND WATERWAYS TRANSPORTATION*.

Douglas Smith, L., Nauss, M. R., Campbell, F. J., & Sweeney II, C. D. (2009). *Triangulation of Modeling Methodologies for Strategic Decisions in an Inland Waterway Transportation System*.

Esmalian, A., Yuan, F., Rajput, A. A., Farahmand, H., Dong, S., Li, Q., ... & Mostafavi, A. (2022). Operationalizing resilience practices in transportation infrastructure planning and project development. *Transportation Research Part D: Transport and Environment*, *104*, 103214.

Felde, J. Zum, Alias, C., & Goudz, A. (2022). Comparing generic and dedicated tools of discrete-event simulation for examining inland waterway transportation services. *2022 IEEE 6th International Conference on Logistics Operations Management, GOL 2022*. https://doi.org/10.1109/GOL53975.2022.9820153

Gopal, P. R. C., & Thakkar, J. (2012). A review on supply chain performance measures and metrics: 2000-2011. In *International Journal of Productivity and Performance*

Management (Vol. 61, Issue 5, pp. 518–547). https://doi.org/10.1108/17410401211232957

Heerkens, H. met Winden, A. van (2017). Solving Management Problems Systemetically Groningen: Noordhoff Uitgevers. ISBN: 978-90 01-88795-7.

Henry, D., & Ramirez-Marquez, J. E. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering & System Safety*, *99*, 114-122.

Holling, C. S. (1973). Resilience and stability of ecological systems.

Klein, A., Hilster, D., Scholten, P., Van Wijngaarden, L., Tol, E., & Otten, M. (2021). *STREAM Freight Transport 2020* [Report, pg. 57]. CE Delft. https://www.cedelft.eu

Ladyman, J. (2002). Understanding philosophy of science. Routledge.

Lenhard, J., Lücking, H., & Schwechheimer, H. (2006). Expert knowledge, Mode-2 and scientific disciplines: two contrasting views. Science and Public Policy, 33(5), 341-350.

Netherlands Code of Conduct for Research Integrity | NWO. (n.d.). NWO. https://www.nwo.nl/en/netherlands-code-conduct-research-integrity

Hosseini, S., & Ivanov, D. (2022). A new resilience measure for supply networks with the ripple effect considerations: a Bayesian network approach. *Annals of Operations Research*, *319*(1), 581–607. https://doi.org/10.1007/s10479-019-03350-8

Hosseini, S., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E: Logistics and Transportation Review*, *125*, 285–307. https://doi.org/10.1016/j.tre.2019.03.001

Kort, & Bert. (n.d.). *STUURGROEP MANAGEMENT WATERCRISES EN OVERSTROMINGEN Handleiding verdringingsreeks*. www.helpdeskwater.nl.

Omer, M., Mostashari, A., Nilchiani, R., & Mansouri, M. (2012). A framework for assessing resiliency of maritime transportation systems. *Maritime Policy & Management*, *39*(7), 685-703.

Port of Twente: logistieke hotspot in Europa | Port of Twente. (n.d.). Port of Twente. https://www.portoftwente.com/

Saisridhar, P., Thürer, M., & Avittathur, B. (2024). Assessing supply chain responsiveness, resilience and robustness (Triple-R) by computer simulation: a systematic review of the literature. In *International Journal of Production Research* (Vol. 62, Issue 4, pp. 1458–1488). Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2023.2180302

Segovia, P., Pesselse, M., Van Den Boom, T., & Reppa, V. (2022). Scheduling inland waterway transport vessels and locks using a switching Max-Plus-Linear systems approach. IEEE

Open Journal of Intelligent Transportation Systems, 3, 748–762. https://doi.org/10.1109/ojits.2022.3218334

Smith, L. D., Sweeney, D. C., & Campbell, J. F. (2009). Simulation of alternative approaches to relieving congestion at locks in a river transportion system. *Journal of the Operational Research Society*, *60*(4), 519–533. https://doi.org/10.1057/palgrave.jors.2602587

Redactie. (2023, May 24). *Twente Corridor gaat vol voor de binnenvaart - Binnenvaartkrant*. Binnenvaartkrant. https://binnenvaartkrant.nl/twente-corridor-gaat-vol-voor-de-binnenvaart

Robinson, S. (2014). Simulation: the practice of model development and use. Bloomsbury Publishing.

University of Twente. (2023, October 23). Twente researchers make transport chains more reliable using a "digital twin." *Universiteit Twente*. https://www.utwente.nl/en/news/2023/10/1194213/twente-researchers-make-transport-chains-more-reliable-using-a-digital-twin#fiscal-disaster

Verdringingsreeks bij watertekort. (n.d.). Kenniscentrum InfoMil. https://www.infomil.nl/onderwerpen/lucht-water/handboek-water/thema-s/watertekort/verdringingsreeks/

Vinke, F., Turpijn, B., van Gelder, P., & van Koningsveld, M. (2024). Inland shipping response to discharge extremes – A 10 years case study of the Rhine. *Climate Risk Management*, *43*. https://doi.org/10.1016/j.crm.2023.100578

Vinke, F., van Koningsveld, M., van Dorsser, C., Baart, F., van Gelder, P., & Vellinga, T. (2022). Cascading effects of sustained low water on inland shipping. *Climate Risk Management*, *35*. https://doi.org/10.1016/j.crm.2022.100400

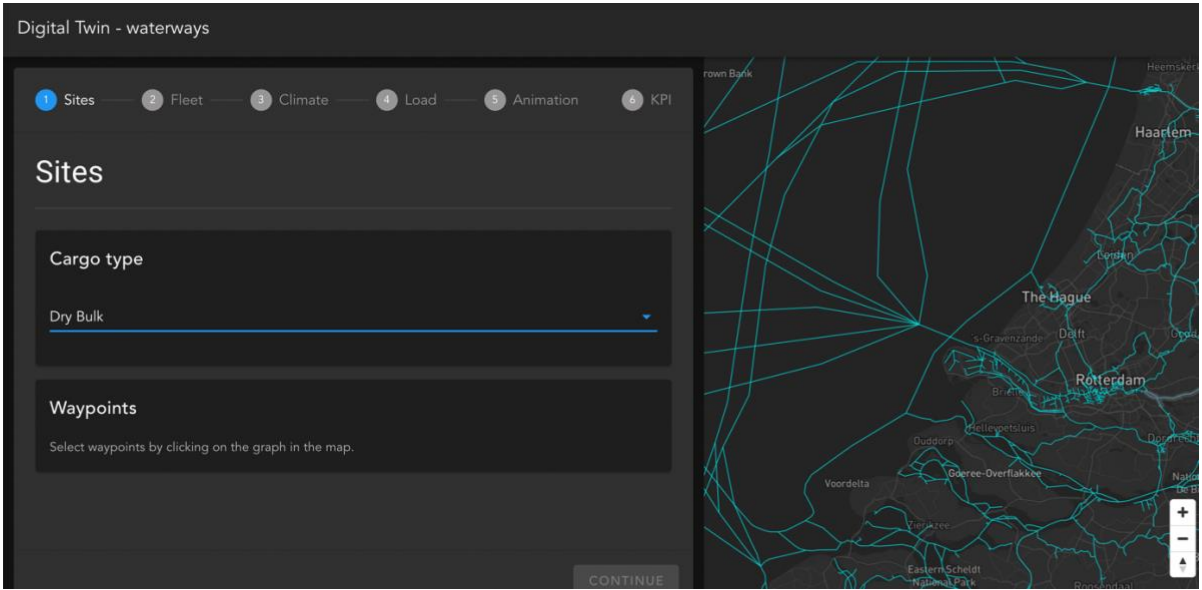
Wang, N., & Yuen, K. F. (2022). Resilience assessment of waterway transportation systems: Combining system performance and recovery cost. *Reliability Engineering and System Safety*, *226*. https://doi.org/10.1016/j.ress.2022.108673

Water management in the Netherlands The Kreekraksluizen in Schelde-Rijnkanaal. (n.d.). https://www.helpdeskwater.nl/publish/pages/165190/rij_8475_watermanagement_en_dv_1.pdf

Zhou, Y., Wang, J., & Yang, H. (2019). Resilience of transportation systems: concepts and comprehensive review. *IEEE Transactions on Intelligent Transportation Systems*, *20*(12), 4262-4276.

Appendix A

Interface of the digital twinning model. The set up is similar for both the container cargo type and the dry bulk cargo type, except that the unit of measurement when configuring the cargo load and loading rates for dry bulk is in tonness, and for containers it is in TEUs.

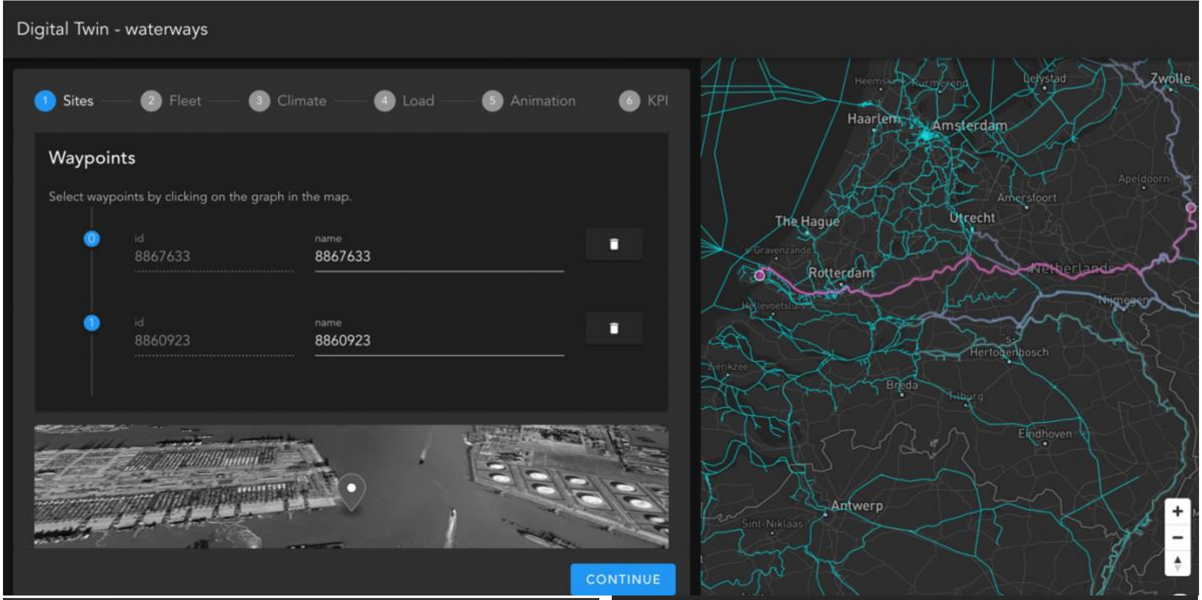


Sites

Cargo type: Dry Bulk

Waypoints

Select waypoints by clicking on the graph in the map.

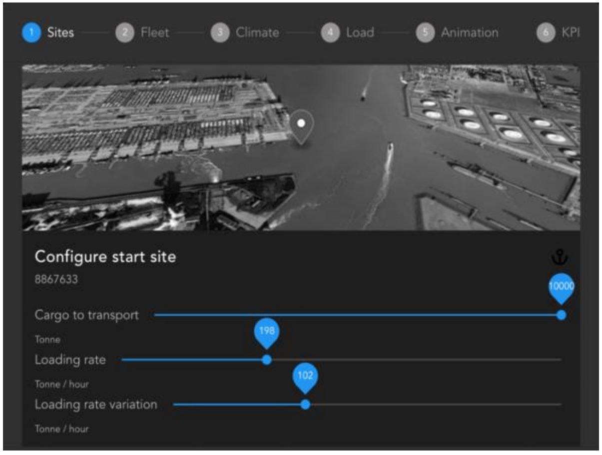


Waypoints

Select waypoints by clicking on the graph in the map.

0 id 8867633 name 8867633

1 id 8860923 name 8860923



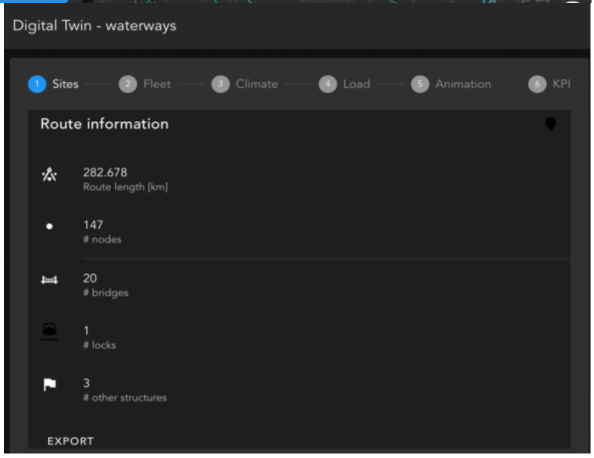
Configure start site

8867633

Cargo to transport: 10000 Tonne

Loading rate: 198 Tonne / hour

Loading rate variation: 102 Tonne / hour



Route information

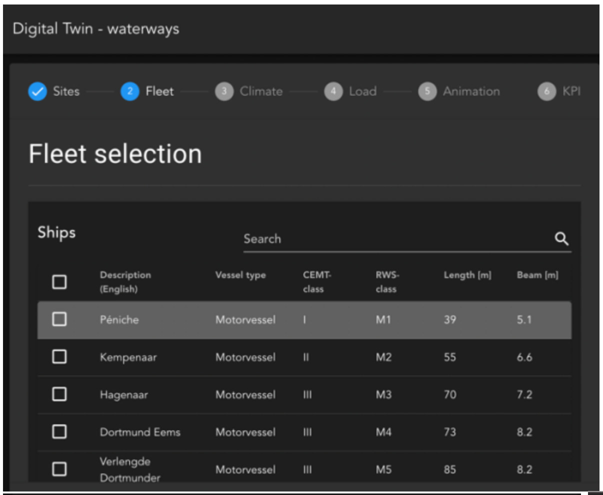
282.678 Route length [km]

147 # nodes

20 # bridges

1 # locks

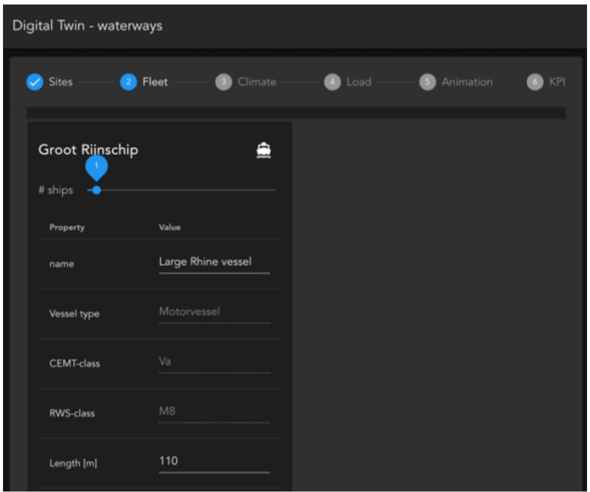
3 # other structures



Fleet selection

Ships

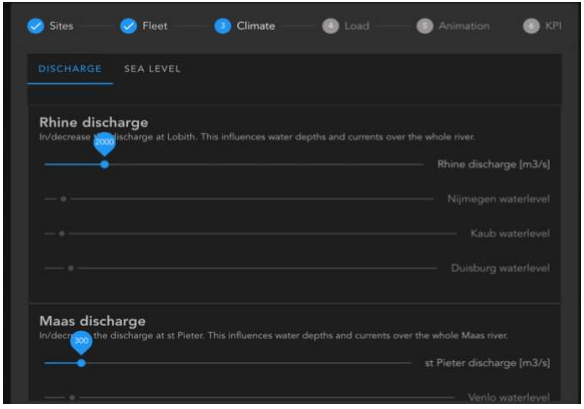
☐	Description (English)	Vessel type	CEMT-class	RWS-class	Length [m]	Beam [m]
☐	Péniche	Motorvessel	I	M1	39	5.1
☐	Kempenaar	Motorvessel	II	M2	55	6.6
☐	Hagenaar	Motorvessel	III	M3	70	7.2
☐	Dortmund Eems	Motorvessel	III	M4	73	8.2
☐	Verlengde Dortmunder	Motorvessel	III	M5	85	8.2



Groot Rijnschip

ships: 1

Property	Value
name	Large Rhine vessel
Vessel type	Motorvessel
CEMT-class	Va
RWS-class	M8
Length [m]	110



Rhine discharge

In/decrease [illegible] discharge at Lobith. This influences water depths and currents over the whole river.

Rhine discharge [m3/s]: 2000

Nijmegen waterlevel

Kaub waterlevel

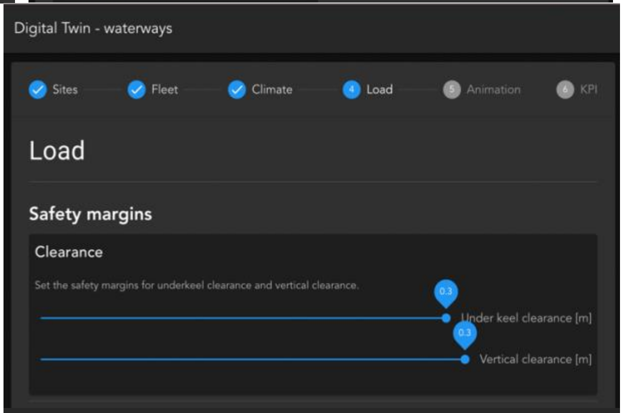
Duisburg waterlevel

Maas discharge

In/decr [illegible] the discharge at st Pieter. This influences water depths and currents over the whole Maas river.

st Pieter discharge [m3/s]: 300

Venlo waterlevel



Load

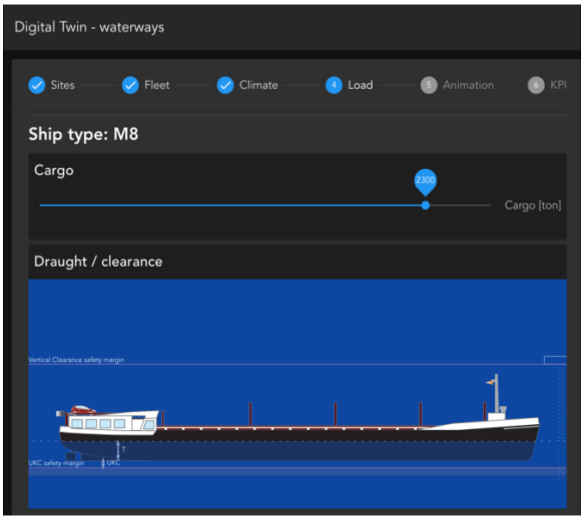
Safety margins

Clearance

Set the safety margins for underkeel clearance and vertical clearance.

Under keel clearance [m]: 0.3

Vertical clearance [m]: 0.3

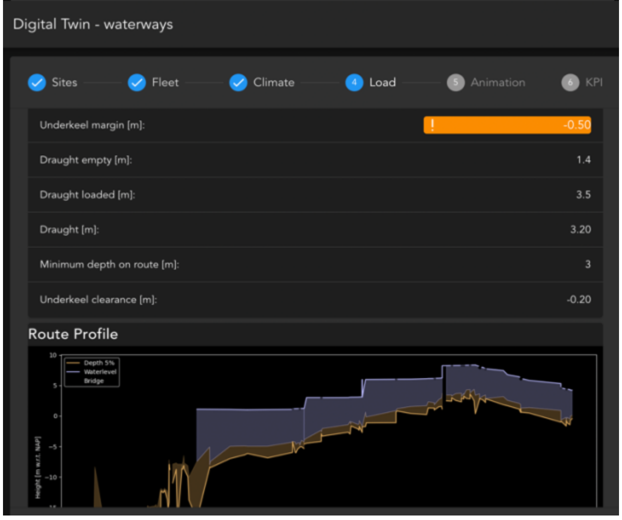


Ship type: M8

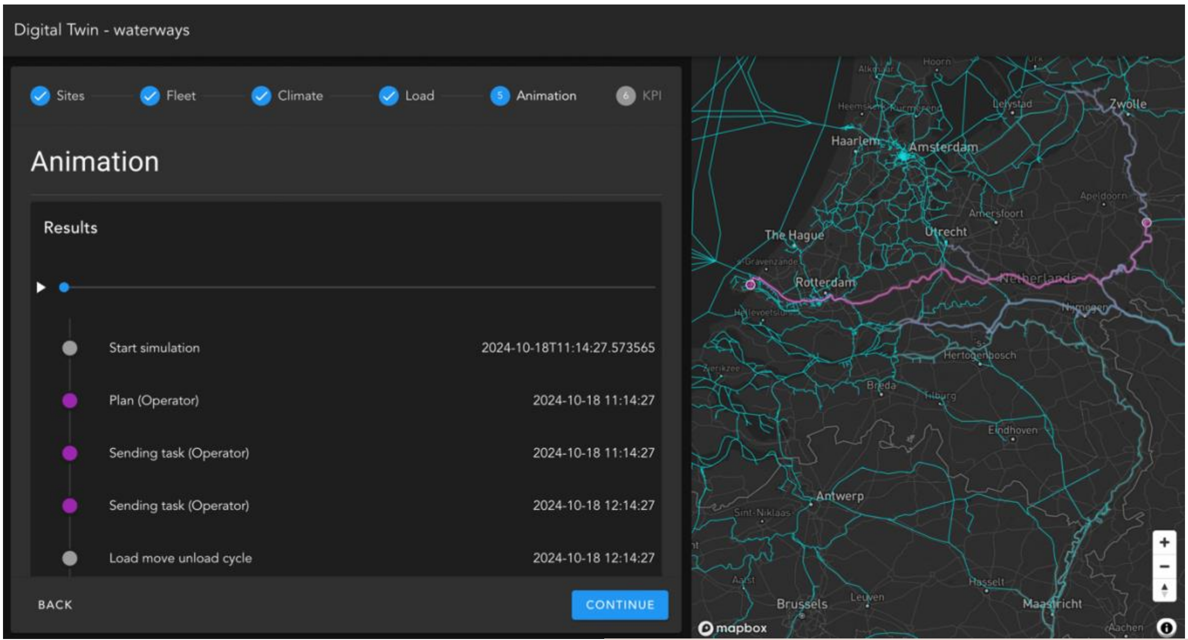
Cargo

Cargo [ton]: 2300

Draught / clearance



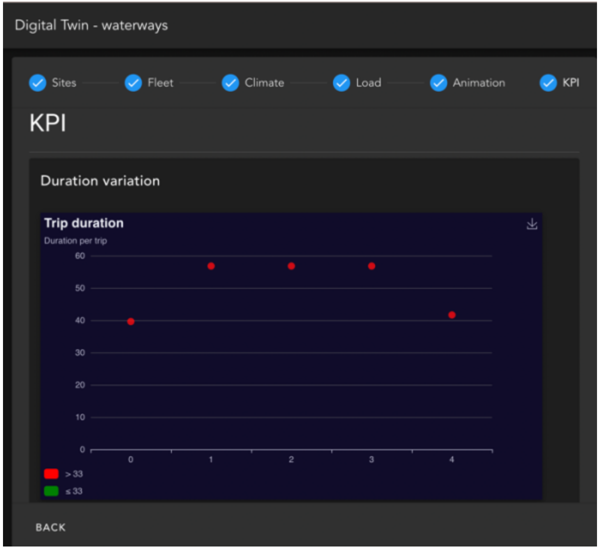
Underkeel margin [m]:	! -0.50
Draught empty [m]:	1.4
Draught loaded [m]:	3.5
Draught [m]:	3.20
Minimum depth on route [m]:	3
Underkeel clearance [m]:	-0.20



Animation

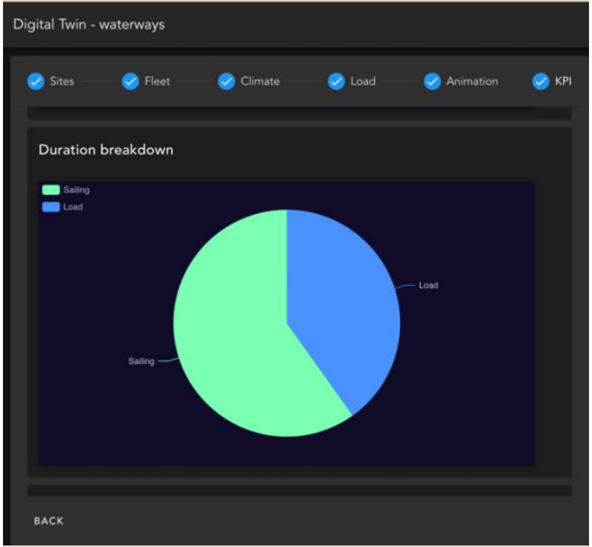
Results

Start simulation	2024-10-18T11:14:27.573565
Plan (Operator)	2024-10-18 11:14:27
Sending task (Operator)	2024-10-18 11:14:27
Sending task (Operator)	2024-10-18 12:14:27
Load move unload cycle	2024-10-18 12:14:27

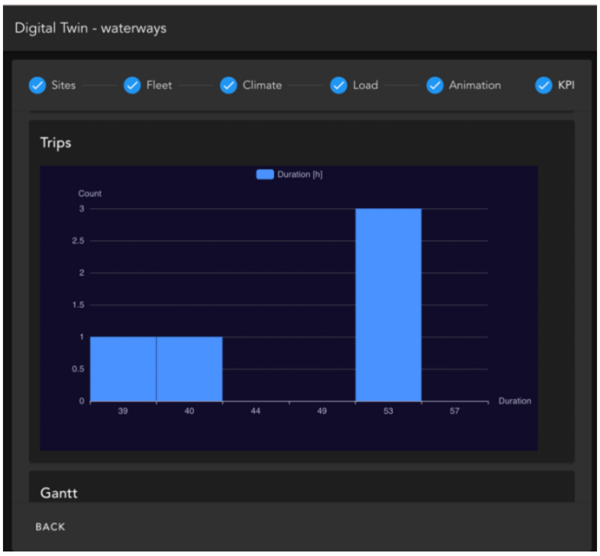


KPI

Duration variation

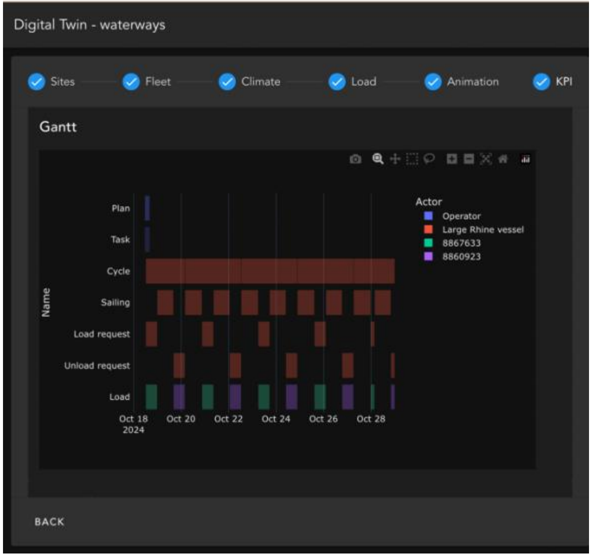


Duration breakdown



Trips

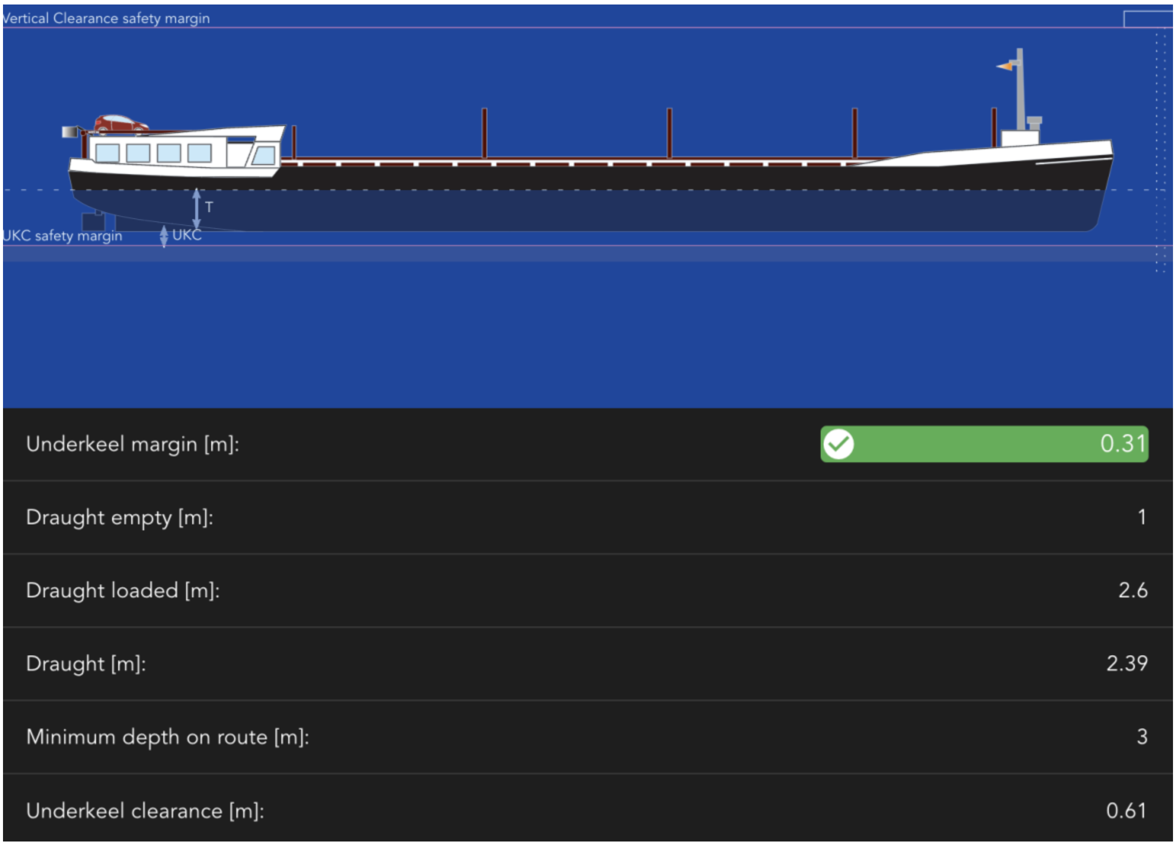
Gantt



Gantt

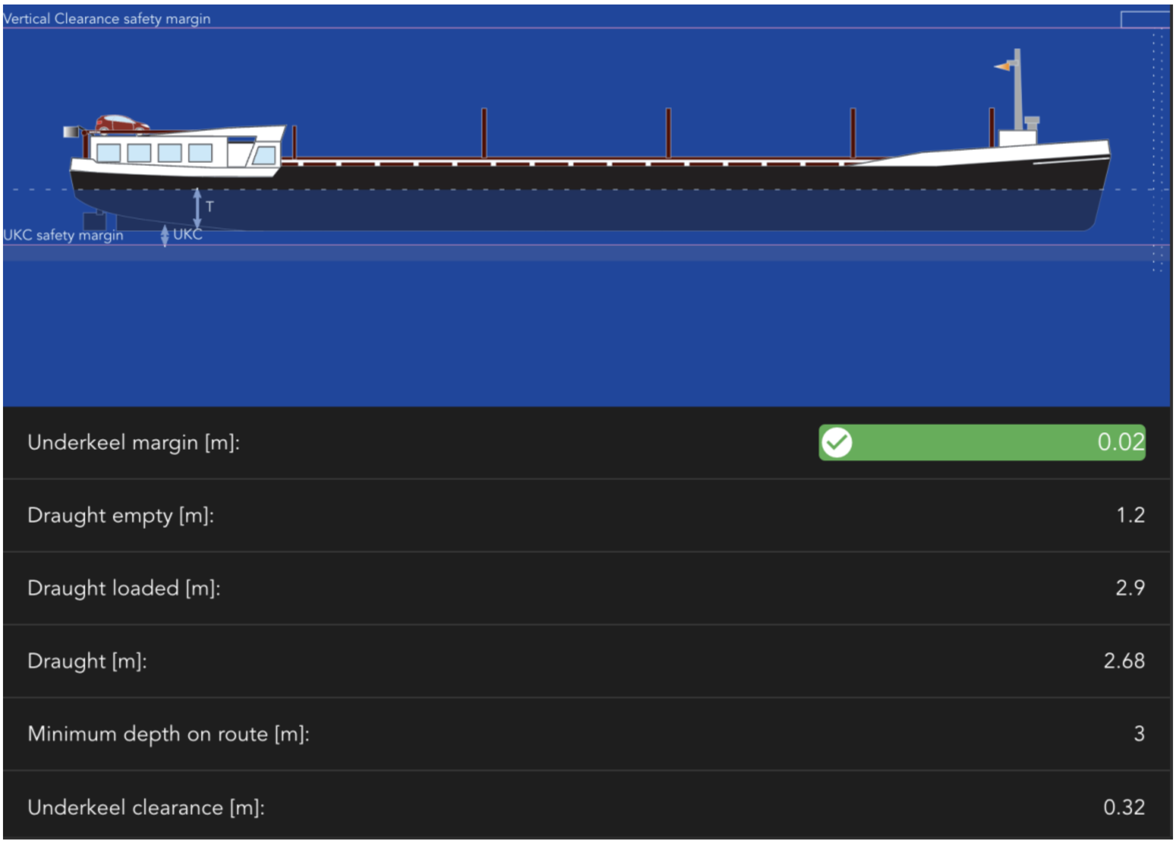
Appendix B

Draught clearnace measurements per ship class.



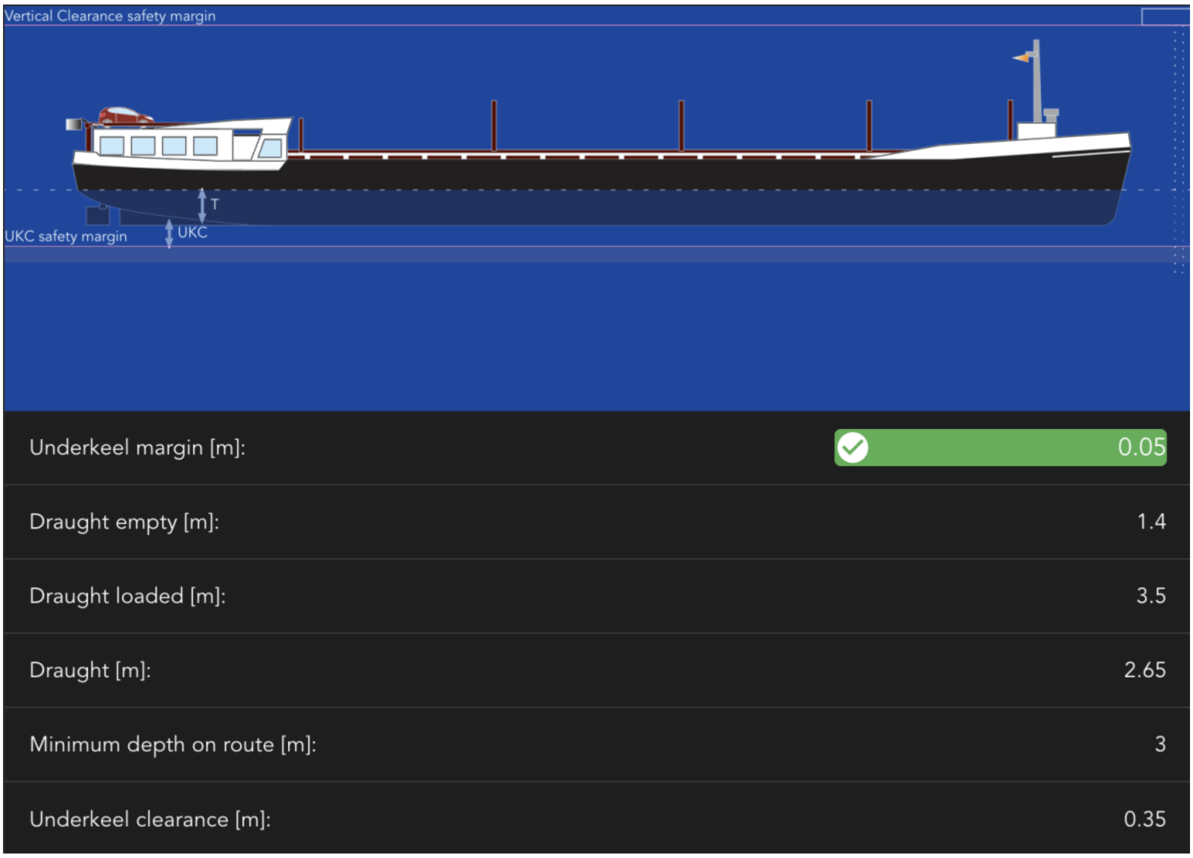
Underkeel margin [m]:	✓ 0.31
Draught empty [m]:	1
Draught loaded [m]:	2.6
Draught [m]:	2.39
Minimum depth on route [m]:	3
Underkeel clearance [m]:	0.61

- Fleet – M2 x2, Capacity – 500 tonnes



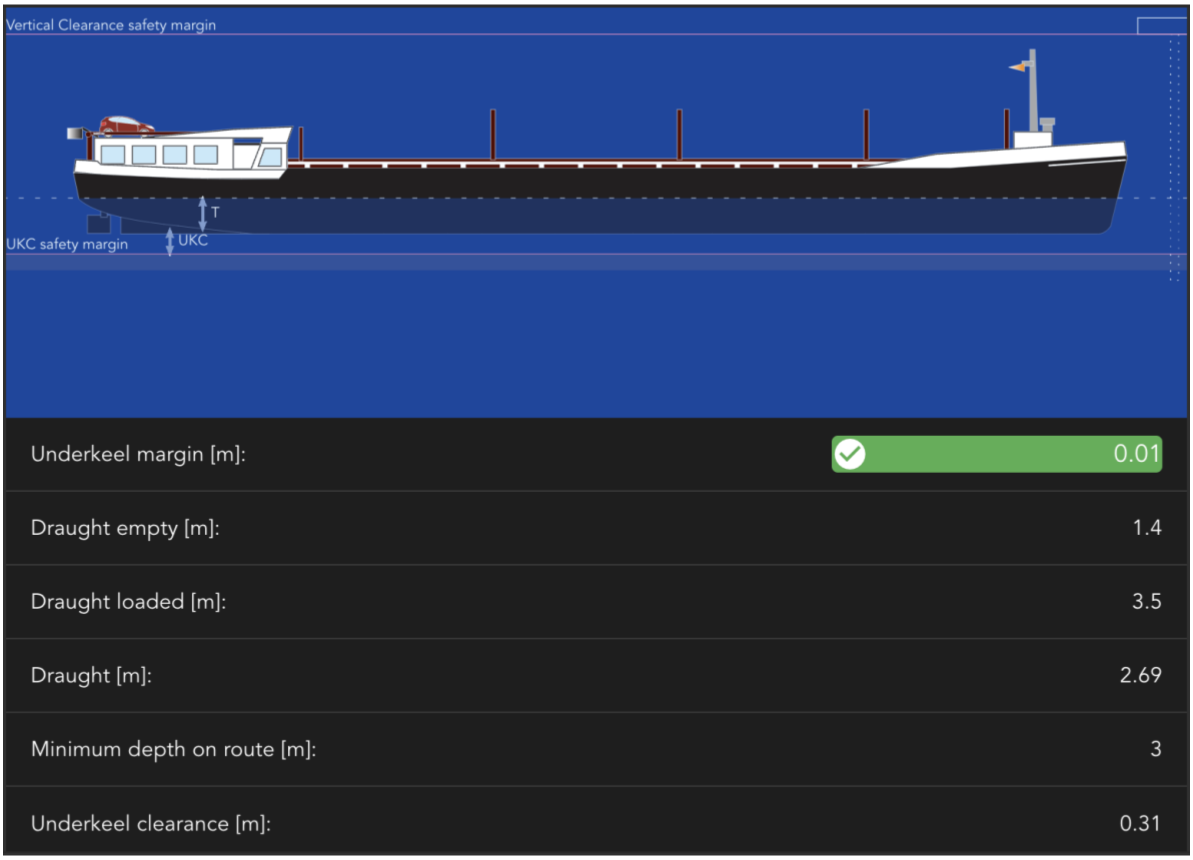
Underkeel margin [m]:	✓ 0.02
Draught empty [m]:	1.2
Draught loaded [m]:	2.9
Draught [m]:	2.68
Minimum depth on route [m]:	3
Underkeel clearance [m]:	0.32

- Fleet – M6 x1, Capacity – 1300 tonnes



Underkeel margin [m]:	✓ 0.05
Draught empty [m]:	1.4
Draught loaded [m]:	3.5
Draught [m]:	2.65
Minimum depth on route [m]:	3
Underkeel clearance [m]:	0.35

- Fleet – M8 x1, Capacity – 1600 tonnes



Underkeel margin [m]: ✓ 0.01

Draught empty [m]: 1.4

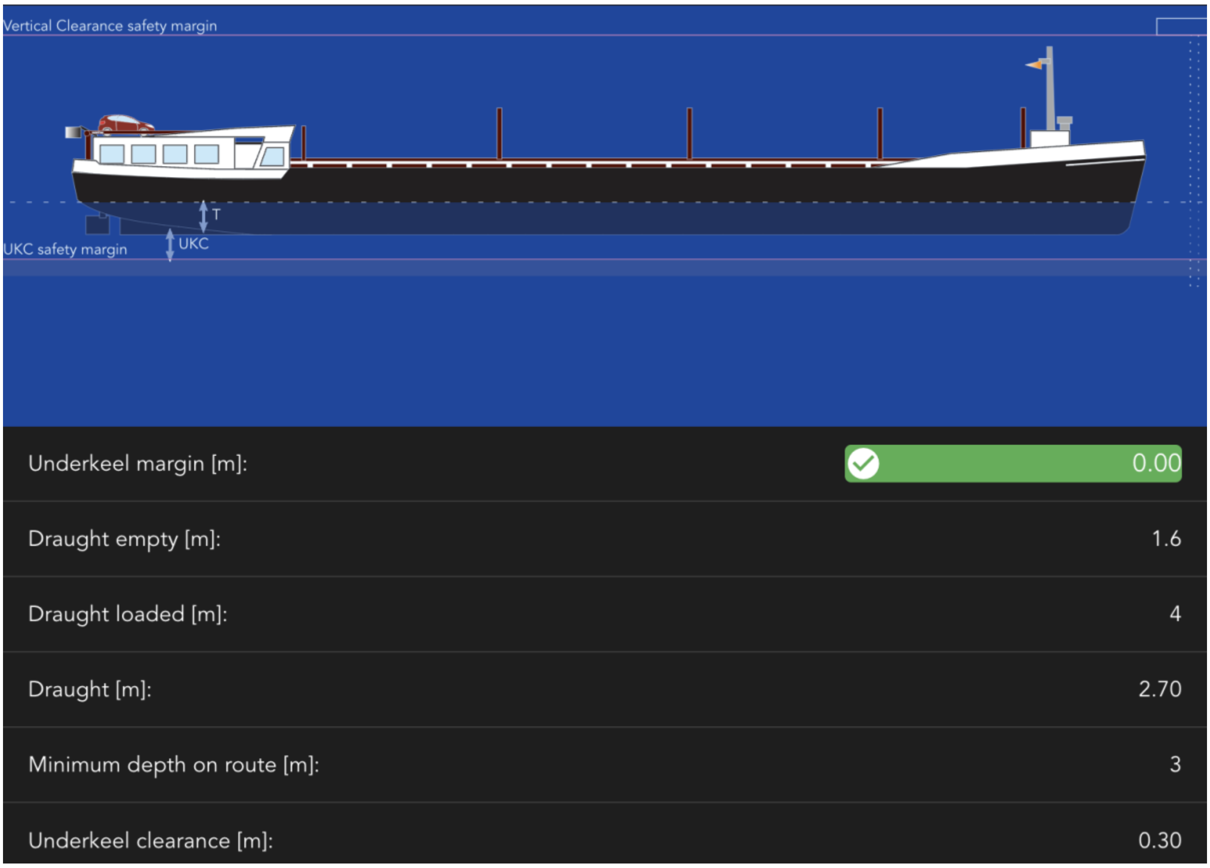
Draught loaded [m]: 3.5

Draught [m]: 2.69

Minimum depth on route [m]: 3

Underkeel clearance [m]: 0.31

- Fleet – M9, Capacity – 2400 tonnes



Underkeel margin [m]: ✓ 0.00

Draught empty [m]: 1.6

Draught loaded [m]: 4

Draught [m]: 2.70

Minimum depth on route [m]: 3

Underkeel clearance [m]: 0.30

- Fleet – M12, Capacity – 2700 tonnes

Appendix C

Search matrix for systematic literature review

Keywords	Related terms/synonyms	Broader terms	Narrower terms
(Experiments	Experiment*, test, analysis*, research, study*	Practice*,	“Trial run”)
(“Simulation study”	“Simulation model*”, “simulation* analysis”, “digital imitation”	“Illustration”	“Digital twin”, “Computer simulation”)
(Evaluating	Evaluate*, assess*, measure*, value*, analyze*, estimate*, test*	Investigate*, Weigh*	Quantify*, “impact of”, “influence of”, “influence of”)
(Methods	Method*, approach*, technique*, practice*, strategy*, procedure*,	Means, mechanism*, system*	Device*, “modus operandi”, tactic*, “new approaches”, “innovative practices”)
(Increasing resilience	“Increase* resilience”, “Increase* performance”, “greater resilience”, “enhance* resilience”, “strengthen* resilience”, “build* resilience”	Flexibility	“Enhance* Performance”, “shipping resilience strategies)
(“Inland shipping”	“Inland water transport”, “inland waterways”, inland navigation”, “inland water transport”	Shipping, freight	“River traffic”)
(Canal	channel, “water passageway”, “canal levels”	Waterway,	“Joint corridor”)
(“Low water level*”	“Low water line”, “low water mark”, “low water”	“Receding water depth”	“Water depletion”, drought, “channel conditions”, “waterway conditions”)

Inclusion Criteria and Exclusion Criteria

Inclusion Criteria	Motivation

Published in the last 30 years	Simulation studies for inland shipping have been done since multiple decades ago, however, the understanding of resilience of supply chains has only been explored since the mid 1990's so about 30 years ago.
Disciplines: engineering, business, management and accounting	the simulation of inland waterways covers both engineering practices due to the tools used and optimization models, and the management discipline due to the organizational aspect of supply chain entities.
Exclusion Criteria	**Motivation**
Not published in English	This research will be conducted in English.
Anything that is not peer reviewed	Important for meeting the academic requirements recommended by the SLR workshops.
Not specific to simulating inland waterway systems/transportation and/or resilience	This was important because of the need to find suitable experimental methods for my research and indicators that would quantify supply chain resilience which on its own can be quite abstract to understand.

Databases

Database	**Motivation**
Scopus	Recommended in SLR workshops. It is an extensive database covering multiple disciplines including science, engineering, and management, I have used it before, so it was easy to use. The availability of research analytics like citation metrics helped with choosing papers I was sure were academically peer reviewed.
ScienceDirect	I had similar reasons of using this database as I did Scopus. I will also add that ScienceDirect is easier to use due to a better user interface.
LISA	Using the university's database helped with finding academic sources similar to my research from the Netherlands, which was particularly useful given I am using a digital twin that simulates the Dutch waterways.

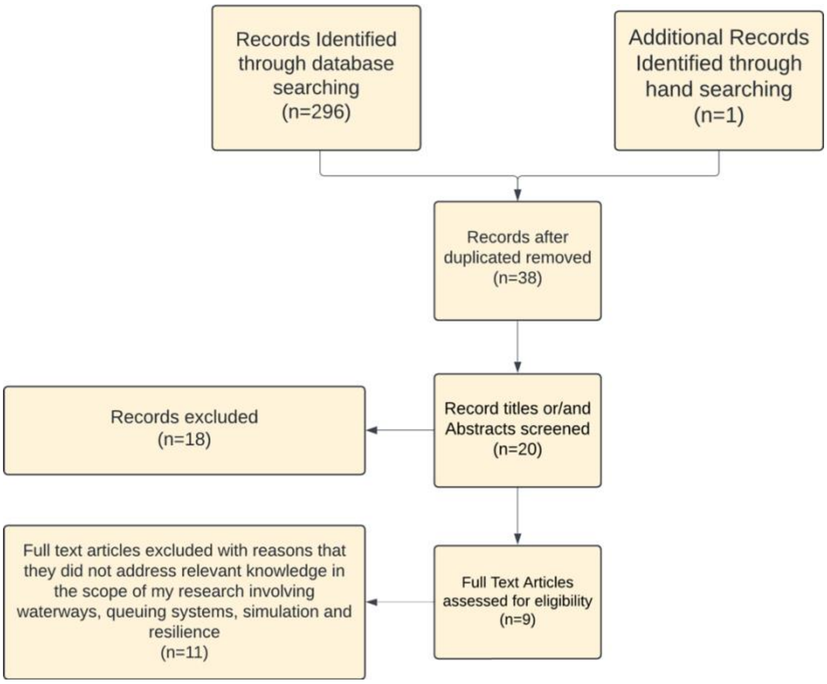
Search log and search terms

Date	Where did I search?	Search String	Filters	Number of hits/relevancy
10 – 04 - 2024	Scopus	("Simulation study" OR "Simulation models" OR "Computer simulation" OR "Digital twin") AND ("Inland shipping" OR "Inland water transport" OR "Inland waterways" OR "Inland navigation") AND ("resilience" OR "performance enhancement")		170 hits, general prompt that retrieved a lot of articles on simulation and many to do with transportation and water infrastructure, some articles about GHG and operations.
14 – 04 - 2024	LISA	("Evaluate" OR "Assess" OR "Analyze") AND ("techniques" OR "methods" OR "strategies") AND ("Low water levels" OR "Water depletion" OR "drought") AND ("Inland shipping" OR "Inland navigation")		2 hits, a very specific search in the University's online library, resulting in one article and one book. Only the article is useful literature.
17-05-2024	ScienceDirect	("Simulation study" OR "Simulation models" OR "Digital twin") AND ("Inland shipping" OR "Inland water transport" OR "Inland waterways" OR "Inland navigation") AND	Years: 1994-2024	84 hits. A large range of articles still too big to find useful articles.

		("resilience" OR "performance enhancement")		
17-05-2024	ScienceDirect	("Simulation study" OR "Simulation models" OR "Digital twin") AND ("Inland shipping" OR "Inland water transport" OR "Inland waterways" OR "Inland navigation") AND ("resilience" OR "performance enhancement")	Years: 1994-2024 Subject areas – Engineering, Business, Management and Accounting	38 hits, a decrease from the previous iteration using the same query there were 84 hits before adding the filter, which greatly narrowed down the hits of which 8 had titles of useful papers that could inform the methodology of the research being undertaken. Much of the articles included simulations and resilience of infrastructure, but not all with respect to waterways.
21-05-2024	ScienceDirect	("Simulation study" OR "Simulation models" OR "Computer simulation" OR "Digital twin") AND ("Inland shipping" OR "Inland water transport" OR "Inland waterways" OR "Inland navigation") AND ("resilience")	Years: 1994-2024 Subject areas – Engineering, Business, Management and Accounting	40 hits. Many relevant articles come up. There are more topics in line with digital twins, so this was promising. I observed that many of the papers I already found in the previous query came up once more. There are still some articles to do with port architecture.

Screening Flowchart

The flow chart below in figure 5 illustrates the process of coming down to 9 main articles that I used for my systematic literature review to answer the research questions presented above in the main project proposal. I filtered out the initially by removing any duplicates from my search queries, especially ones that had nothing to do with the scope of my research. This left me with 38 papers to choose from. It should be noted that there was one paper provided by my thesis supervisor with respect to the research that was done for digital supply chain twins, therefore this was the article I marked as found by hand searching. I then skimmed through the abstracts of the 38 articles if I thought the title of the article was within the scope of my research objectives, leading to 18 papers being discarded, and leaving 20 papers. It took me some time to read through the 20 articles, but ultimately, I was left with 9 papers for my systematic literature review, as well as for finding literature to support my choice of methodology and research design.



Abstract

This thesis explores strategies to improve resilience in the Twente Corridor, an important inland shipping route in the Netherlands, against climate-induced water level extremes such as droughts and floods. Using a digital twin model of Dutch waterways developed by Deltares, the study simulates the impact of varying water conditions on container and dry bulk shipping performance. Key performance indicators were analyzed under different scenarios, including transit time, vessel utilization, and energy consumption. This research underscores the importance of simulation-based planning in addressing climate stress in inland logistics corridors.

Findings revealed significant disruptions under extreme water levels, such as increased transit times, inefficient vessel utilization, and higher energy consumption. Proposed resilience-building strategies include adaptive vessel scheduling, and prioritizing vessel

classes tailored to specific water conditions. These strategies aim to optimize operations, reduce bottlenecks, and improve fuel efficiency.

The study provides actionable insights for stakeholders in the Twente region, contributing to a resilience framework for inland waterways. Recommendations include simulating more scenarios with different vessel types under water-level extremes and developing priority scheduling rules for enhanced adaptability.