Stress testing the Nautical Chain: A Discrete Event Simulation to Improve The Resilience of The Nautical Chain

A Case Study Of The Port Of Rotterdam

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Graduation committee:

Chairperson	: Prof.dr.ir. L.A. Tavasszy
First Supervisor	: Dr. S. Fazi
Second Supervisor	: Dr. L.J. Kortmann
Advisor	: Ms. S. Nikghadam

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K.K. Baggers

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Kevin Baggers

Student number: 4364236

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Graduation committee

Chairperson	: Prof.dr.ir. L.A. Tavasszy, Engineering Systems and Services
First Supervisor	: Dr. S. Fazi, Transport & Logistics
Second Supervisor	: Dr. L.J. Kortmann, Multi-Actor Systems
Advisor	: S. Nikghadam, Engineering Systems and Sevices

Preface

This research is performed to get a Master of Science degree from the study Engineering and Policy Analysis (EPA) at the Technical University of Delft. I want to thank Lorí Tavasszy for his input and guidance during the mid-term and green-light meetings and giving me the opportunity to graduate on such an interesting topic. I want to thank Stefano Fazi, Rens Kortmann and Shahrzad Nikghadam for their time and effort with the supervision of this thesis. I want to thank Ms. Shahrzad Nikghadam specially for the many hours we spent together besides her own research project. Also, her expertise and knowledge helped greatly with the construction of the model. I really enjoyed working on this thesis, where the committee from the TU Delft helped me achieving my goals and steering me in the right direction. I found modelling to be an addictive task, where I kept the motivation to endlessly improve the simulation model. Luckily, Ms. Nikghadam helped me focussing on the other aspects of the thesis too, besides the modelling. I learned a lot about the processes and influence of the Nautical Chain in ports, and the state of resilience of the Nautical Chain. Also, I improved my modelling and reporting skills by a great margin due to this thesis.

Last, I want to thank my family and friends for supporting me during this thesis, and a special thanks to my parents who made this whole educational achievement possible. A special thanks goes out to Martijn Marner, who helped me with several aspects of the Microsoft Office software like this Word document and Excel graphs. I hope you enjoy reading about resilience in the Port of Rotterdam, and that you will be as surprised as I am with the results generated in this research!

Summary

Maritime logistics is very important for the international volume of trade. In this maritime supply chain ports are critical in cargo transhipment. When a port is unable to serve vessels, the maritime supply chain is impacted. Therefore, it is important that ports function reliably to keep the international trade going. However, ports are vulnerable for disruptions. The Suez Canal blockage and its effects on ports, the Corona virus outbreak impacting the labour force, as well as the backlogged trail of ships at the port of Long Beach are just some examples of disruptions in the past years. Therefore, there is an urgent need for research to understand and improve the resilience of ports.

Ports provide a variety of services to vessels, including traffic management, piloting, towage and mooring. Together, these services can be understood as a chain which is called the Nautical Chain, since the services are dependent on each other. The Nautical Chain can be seen as a self-organising ecosystem of multiple actors, namely the pilot organisations, tugboat companies, harbour master and boatmen. This research looks at the individual effect that an actor of the Nautical Chain can have on the resilience of the whole Nautical Chain system. Also, combined effort of the actors of the Nautical Chain is tested to see the influence on the resilience of the Nautical Chain. With the insights from the resilience of the Nautical Chain, the resilience of the Nautical Chain and thus the maritime supply chain can be improved.

A literature review is conducted on port resilience, the Nautical Chain and disruptions in ports to see the current state of scientific knowledge on the resilience of the Nautical Chain. From the literature on the Nautical Chain a lack of research on the resilience of this chain came forward, since only on the efficiency and the effects of collaboration have been studied. It is therefore needed to first define and conceptualize the Nautical Chain in the scope of resilience. Also, it is not yet known how to model the Nautical Chain and measure the resilience of the Nautical Chain. It is therefore not known what the resilience of the Nautical Chain is and how to improve the resilience of the Nautical Chain, which is the gap this research addresses.

This knowledge gap leads to the main research question and sub-questions. The main research question this research aims to address is:

How to measure and improve the resilience of the Nautical Chain?

To answer this main research question, the following sub-questions are used:

1. How to define Nautical Chain resilience?
2. What kind of disruptions can be expected in ports?
3. Which actors and processes determine the resilience of the Nautical Chain?
4. How to model the Nautical Chain?
5. What is the current state of resilience in the Nautical Chain?
6. Which strategies are recommended to improve the resilience of the Nautical Chain?

Sub question 1, 2 and 3 are answered by conducting a literature review. Sub-question 4, 5 and 6 are answered by a simulation study.

For measuring the resilience of the Nautical Chain the average time in system of vessels in the port is used as the system performance metric. In this research, resilience has been defined as the value of the deviation from the business-as-usual value. Therefore, two metrics have been identified determining the size of the deviation: the maximum deviation from the business-as-usual value and the time it takes from the end of the disruption to the business-as-usual value. Here, the average time in system of vessels during normal

operation of the port is the business-as-usual value. The area under the graph which is the deviation from the business-as-usual value is the metric of the resilience. Improving the resilience can then be found in reducing the time it takes to get back to the business-as-usual value or reducing the maximum impact on the system performance. Both these mitigation strategies reduce the area under the graph, improving the resilience. With this resilience metric, the resilience of the Nautical Chain can be measured, and improvements of this resilience can be measured.

The following disruptions have been chosen to include in this research: accident, cyber-attack, pandemic, Suez Canal blockage and extreme weather. Based on the discovery of possible disruptions at ports, these disruptions have been chosen to include in this research. Inclusion is based on the effect of the disruption on the Nautical Chain system, where only disruptions affecting the Nautical Chain system have been included. Also, a disruption is only added when the effect of the disruption on the Nautical Chain system is not yet included. Therefore, this set of disruptions show the effects on the resilience in a wide spectrum.

It has been chosen to include the following actors in this research: the harbour master, vessels, pilots, tugs and terminals. With this selection of actors, the following activities are included:

- Sailing
- Anchoring
- Boarding/deboarding pilot
- Connecting/disconnecting tugs
- Loading and unloading

With the first 3 sub-questions answered, the simulation model was constructed. It has been chosen to use Discrete Event Simulation (DES) in this research, since this simulation technique is well suited to model queues. In this system, there are three queues: pilot queues, tug queues and terminal queues.

With this model, different disruptions have been tested. The effect of each disruption on the Nautical Chain system is:

- Accident: this simulates an event at the entrance of a branch in the port (the Maasvlakte area), which make the affected terminals unable to handle incoming vessels.
- Cyber-attack: this simulates a cyber-attack at the terminals in the Calland channel in port, making the affected terminals unable to handle vessels.
- Pandemic: this scenario simulates a three week pandemic, halving the amount of tugs and pilots during these three weeks. Also, the unloading times increase at terminals.
- Suez Canal blockage: this scenario simulates blockages at other ports or infrastructures, leading to fluctuations in vessel arrival.
- Weather: this simulates extreme weather conditions rendering the port water infrastructure unable to serve vessels, thus closing the port.

In all scenarios the average time in system increased compared to the business-as-usual value. The increase of the average time in system differed between the scenario's, with the highest value for the cyber-attack, followed by the pandemic, accident, weather and the lowest value for the Suez Canal blockage. Different mitigation strategies have been tested to give insight in the effect on the ports resilience. These strategies have been categorized in two categories: policy mitigation strategies and capacity mitigation strategies.

Policy mitigation strategies are: increasing average speed, largest vessel first, less tugs first and smallest vessel first. The last three of these strategies are vessel priority strategies. The results show that increasing the average speed has a stable and improving effect on the resilience, with an improvement of 3.5% as minimum and 21% as maximum. The vessel priority strategies yielded different results. Within these vessel priority strategies, the smallest vessel first preference strategy yielded the best results overall with a maximum improvement of the resilience of 14%. The largest vessel first strategy performed worst, sometimes even having a negative effect on the resilience of up to 19%.

The capacity mitigation strategies consist of: increasing pilots, increasing tugs, and increasing both pilots and tugs simultaneously. Pilots have been increased with 3 and 6 extra pilots. Tugs have been increased with 2 and 5 extra tugs. In the mitigation strategy where both pilots and tugs are increased, the amount of pilots is increased with 6 and the amount of tugs is increased with 5 extra tugs. The results of these strategies showed that in many scenarios, increasing the amount of pilots increases the resilience up to 42%. The difference between the base-case and 3 pilots was larger than between 3 and 6 extra pilots. This shows that not every added pilot has the same contribution, and the effect softens with an increasing amount of pilots. Therefore, the increase of pilots should be depending on the severity of the disruption, and the goals on mitigating the effects of this disruption. Increasing the amount of tugs yielded less result on improving the resilience of the port with a maximum increase in the resilience of 8%. The difference between 2 and 5 extra tugs was also minimal, indicating that increasing the amount of tugs also has a dampening effect with every tug added. Increasing both the amount of pilots and tugs simultaneously resulted in the best results regarding the resilience. This often improved more than the sum of the improvements of 6 extra pilots and 5 extra tugs. The simultaneous increase in pilots and tugs resulted in the largest overall improvement of the resilience, with stable improvements in all scenarios of up to 46%.

The results found in this study can be summarized as followed:

Increasing the average speed yield stable results improving the resilience over all scenario’s. The improvement is the smallest with 3.5% for the pandemic, and largest with 21% for the Suez Canal blockage. In all scenario’s, a simultaneous increase in pilots and tugs yield the best results improving the resilience. The smallest improvement was found in the pandemic scenario with an improvement of 11%, while the largest improvement was found for the weather scenario with an improvement of 46%.

The vessel priority preference mitigation strategies yielded different results depending on the scenarios. The smallest vessel first strategy outperformed the largest vessel first and less tugs first strategies in all scenarios. For the largest vessel first, the results showed a decrease of the resilience of up to 19%, and a maximum improvement of 5% in the cyber-attack scenario. Only in the cyber-attack scenario an improvement was found. In all other scenarios, the resilience decreased with this strategy. For the less tugs first strategy, different results on either improving or decreasing the resilience were found. The best result for the resilience is found in the cyber-attack scenario with an improvement of 9%. The worst result was found in the accident scenario with a decrease of 1%. For the smallest vessel first strategy, the only decrease in the resilience was found in the accident scenario with a decrease of 2%. For the rest of the scenarios the results improved the resilience, maximizing at 14% in the cyber-attack scenario.

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1. Introduction

1.1 Problem definition

Maritime logistics has an 80% share in the volume of international trade in goods, with even higher percentages for developing countries (UNCTAD, 2020). The international trade is increasing year by year, with an overall 0,5% growth in 2019 (UNCTAD, 2020), and this poses problems for many ports (Ngai et al, 2011). The growth of the global trade in 2019 stalled compared to previous years, caused by trade policy tensions including supply-side disruptions, social unrest and low oil demand growth (UNCTAD, 2020). Recent shocks, such as the COVID-19 pandemic and blockage of the Suez canal, disrupted the global supply chains (CNBC, 2021) (Zuidwijk, 2021). Ports are critical infrastructures in several aspects: their impact on the economy is critical, they attract value added services, ports are a critical gateway for various supplies and ports are community builders (Vanlaer et al. 2021). Moreover, ports are vulnerable for disruptions like natural disasters, labour strikes, cybercrime and terrorism (Jiang et al. 2021; Guerrero et al. 2022; Verschuur et al. 2021; Chen et al. 2017). Therefore, it is important to know what effects these disruptions have on the port, and how to deal with these disruptions. How effective a port can deal with disruptions can be measured in the ports' resilience. A definition of resilience by Galbusera et al. (2018) is: '*to plan and prepare for, absorb, respond to, and recover from disasters and adapt to new conditions'*. The important position of ports in the global supply chain and the vulnerability for disruptions ask for resilient and efficient ports to cope with these kind of disruptions and keep the global supply chains functioning

The Nautical Chain is of great importance for the functioning of the port. Ports support the turn-around of vessels with traffic management, piloting, towage and mooring as main services, which are called the Nautical Chain (NC). The process of a vessel's call at a port starts with a vessel agent requesting a berth for the vessel. The Harbour Coordination Centre (HCC) assesses the tactical planning of the ports (water) infrastructure, nautical safety, security and capacity. If all is approved, the vessel contacts the pilot organisation dispatching a pilot, which orders the towboats once on board. Last, boatmen help moor the vessel at the terminal, which ends the NC for incoming voyages. For outgoing voyages, this process is performed in the other direction. When an organisation of the chain cannot deliver, the whole port call process comes to an hold leading to delays for vessels. It is therefore in the interest of the port authority to make sure the Nautical Chain functions reliable. According to Lind et al. (2021) the Nautical Chain can be seen as a self-organising ecosystem of many players. This implies that this system is unable to optimise the operations of the system as a whole. It is therefore important that performance of the Nautical Chain is tested when disruptions happen, since the Nautical Chain is of great importance for the performance of the port.

1.2 Knowledge gap

The literature review showed that no research has been done on the resilience of the Nautical Chain. This literature review can be found in chapter 2. In this review, research regarding the Nautical Chain, supply chain resilience, critical infrastructures and port disruptions have been reviewed. From the Nautical Chain literature a framework of the Nautical Chain came forward from a master thesis of Verduijn (2017). This framework supports the construction of simulation models regarding the Nautical Chain. Nikghadam et al. (2021) looked at information sharing between the actors of the Nautical Chain aimed at mitigating delays in ports. Childerhouse et al. (2020) found that flexibility is a good strategy improving the resilience of supply chains. Also, Jing et al. (2021) constructed a framework considering resilience of the maritime supply chain in a network structure, thus looking at multiple ports. When looking at shipping companies, Abioye et al. (2021) found that an increase in the sailing speed of vessels can, partly, help shipping companies recover their schedule after disruptions. From the literature review it came forward that the research regarding the Nautical Chain currently did not look at resilience of this chain. Supply chain resilience did not look at individual ports or the role of the Nautical Chain. Last, critical infrastructure research did not look at the resilience of the Nautical Chain. In short, the knowledge gap in the literature is therefore the current state of resilience of the Nautical Chain, and the possibilities to improve this resilience. Therefore, this research contributes to the scientific knowledge gap by providing insights in the resilience of the Nautical Chain within the port resilience literature.

1.3 Objective

This research aims to provide insight in the resilience of the Nautical Chain in ports. It is important to understand how different elements of the Nautical Chain influence the resilience, and where improvements in the resilience can be gained. Therefore, this research looks at the current state of resilience of the Nautical Chain in ports, and at the effect of different mitigation strategies to improve this resilience. With the knowledge gained from this research, the resilience of the Nautical Chain and ports can be improved.

Societal relevance

The Port of Rotterdam (PoR) will be the port under study. The Port of Rotterdam had an added value of 6.2% to the whole Dutch economy in 2018 (Port Of Rotterdam, 2018), which indicates the criticality of this infrastructure for the Netherlands. Thereby, the Port of Rotterdam is the largest port of the European Union, with much of the handled cargo designated for countries different then The Netherlands (Bosch et al. 2011). With that, the Port of Rotterdam can be seen as a critical infrastructure in the scope of the European Union as well. Due to the importance of the port, it is highly important that the port functions resiliently. This research will deliver a policy advice for Port Authorities elaborating on the influence of the Nautical Chain on the resilience, and include suggestions on how to improve the resilience of the Nautical Chain.

1.4 Methods

This research has qualitative elements for which a literature review will be performed, and quantitative elements which will be answered by simulation modelling. The literature required for the qualitative elements in this research will be gathered from databases online, like Scopus and Google Scholar. Besides, internal documents will be gathered from experts. After the literature review, part of this study asks for a quantitative answer on measuring and improving resilience. This quantitative part of the research will be answered with a simulation model. For the modelling part, discrete event simulation is chosen. Agent Based Modelling and Continuous modelling were also considered for this research, but were found unfit to model the resilience of the Nautical Chain. The process of handling vessels by the Nautical Chain can be seen as an queuing system where the focus is on how the vessel moves through the system. This is very well suited to be modelled by Discrete Event Simulation. This discrete event model will be constructed in the Simio software package. The model will be on the Port of Rotterdam case, thus data from this port is used. The model will depict the terminals in the port, and the physical water infrastructure including one anchorage area. The vessel, tugs, pilot vessel and pilots are included in the model as moving actors of the Nautical Chain. With this model, several disruptions will be modelled including a pandemic, cyber-attack, extreme weather, an accident and the Suez Canal blockage. With each of these disruptions, several mitigation strategies are tested. These include increasing the amount of pilots, increasing the amount of tugs, allowing higher speeds in the harbour and three vessel entry priority strategies. These vessel priority strategies are: smallest vessels may enter first, largest vessels may enter first and vessels needing the least amount of tugs may enter first. With these disruptions, insight in the current state of resilience of the Nautical Chain can be gained. With the mitigation strategies, insight on the effect of different policies on the resilience of the Nautical Chain can be gained. Together, the methods used in this research will provide insight in the resilience of the Nautical Chain.

1.5 Research questions

Following the knowledge gap and the research objective, the following research question and sub-questions are formulated. The main research question of this research is:

How to measure and improve the resilience of the Nautical Chain?

With this main research question, several sub-questions were constructed:

1. How to define Nautical Chain resilience?
2. What kind of disruptions can be expected in ports?
3. Which actors and processes determine the resilience of the Nautical Chain?
4. How to model the Nautical Chain?
5. What is the current state of resilience of the Nautical Chain?
6. Which strategies are recommended to improve the resilience of the Nautical Chain?

By answering the sub-questions and main research question, a policy advice on improving the resilience of the Nautical Chain can be presented.

1.6 Structure of this report

Figure 1.1 shows the outline of this report. This starts with the literature review in Chapter 2, where literature on the Nautical Chain and resilience will be reviewed. Next, in Chapter 3 the conceptualisation of the system will be discussed together with the methodology. Chapter 4 shows the model implementation. The data will be discussed in Chapter 5, which starts with the model input data followed by calibration, verification and validation. Next, the experimentation will be discussed in Chapter 6. This will start with the base case followed by the setup, base case results, policy results and capacity results for each of the disruptions. The discussion will be in Chapter 7, and this report ends with the conclusion and further research recommendations in Chapter 8.

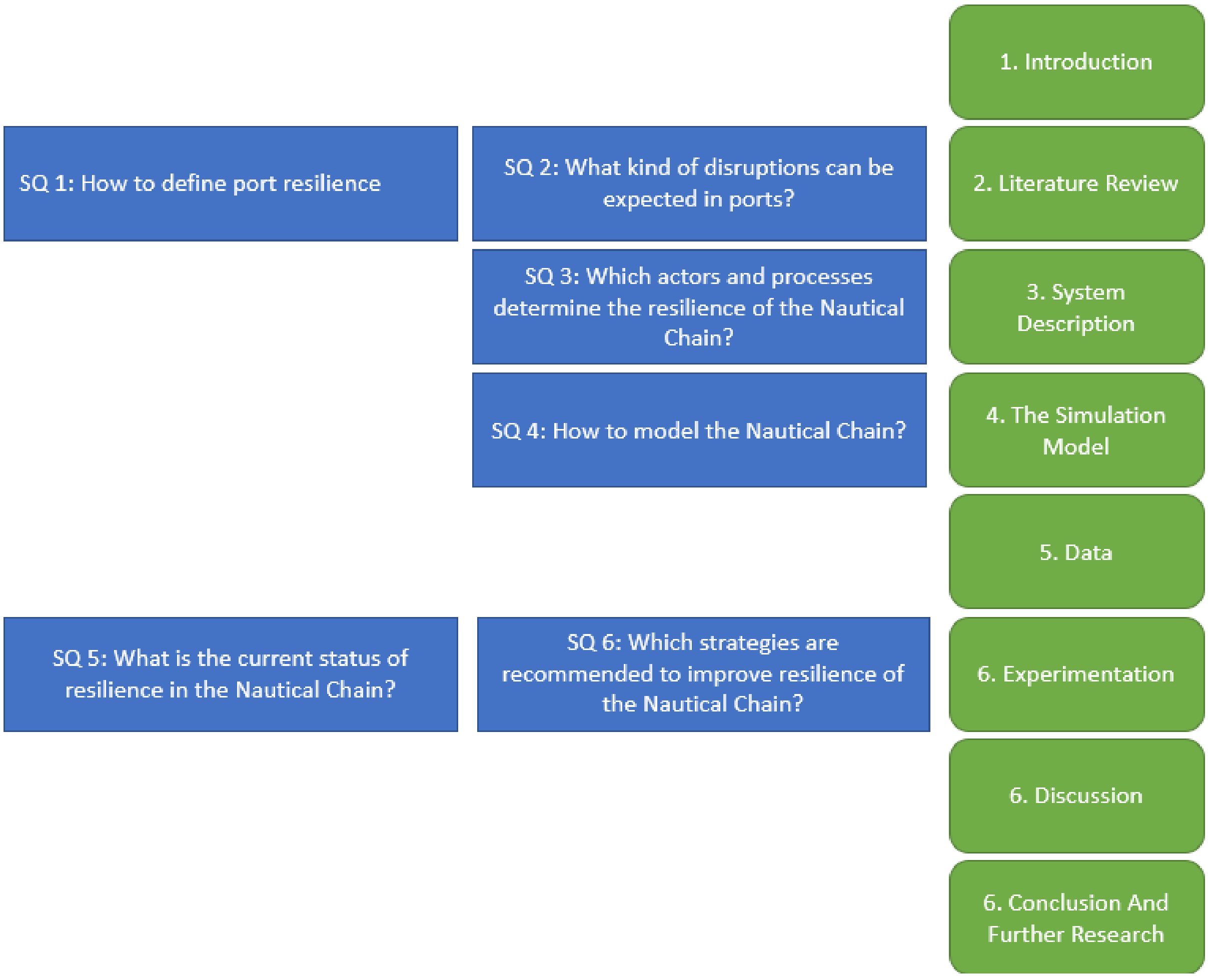


Figure 1.1: Structure Of The Report

2. Literature Review

In this chapter the available literature is reviewed. From this review, the scientific knowledge gap is elaborated upon.

2.1 Literature search

For the search of relevant literature regarding the resilience of the Nautical Chain, multiple search terms have been used in different databases. The databases that have been used are Scopus and Google Scholar. Besides that, the repository of the TU Delft has been consulted to find literature regarding the SWARMPORT project, which researches the Nautical Chain. Search terms used to find literature include: port AND resilience, port AND discrete AND modelling OR modelling AND resilience, port AND disruptions, nautical AND chain AND resilience, and port AND resilience and many more. Selecting the literature for inclusion in this review is based on the title, abstract, conclusion and discussion. The papers found in this literature search haven been categorized in: Nautical Chain, resilience and port disruptions. Together, the insight gained from this literature provides insight for the qualitative parts of this research.

2.2 Nautical chain

The literature regarding the Nautical Chain provide insights in the functioning of this chain, and the current status of the research regarding the Nautical Chain. Verduijn (2017) did his MSc thesis on developing an framework of the Nautical Chain. This framework was constructed by an actor analysis and a process analysis. The goal of this framework is to be used to construct an Agent Based Model (ABM). This thesis therefore provides a large amount of data from the Port of Rotterdam able to use in simulation modelling. In 2021, TNO published the ABM (partly) based on the groundwork of Verduijn (Fransen et al., 2021). This ABM was constructed to be used in studies on the effect of alternative behaviour of the actors of the Nautical Chain on the ports performance. Molkenboer (2020) gave insight in the role information sharing can play in improving the efficiency of the Nautical Chain. GAN (2019) tried to build an Discrete Event Simulation (DES) model to evaluate the performance of the Nautical Chain, which has not been completed. Nikghadam et al. (2021) looked into mitigating delays in port by using information sharing between the actors of the Nautical Chain. Pilots and tugboats were found to have a critical position in port, while terminals have less of a contribution to mitigate delays. Boatmen were found to barely lead to delays in port. Based on the literature on the Nautical Chain it can be concluded that no research on the resilience of this chain has been performed.

2.3 Resilience

In the resilience literature many definitions of resilience are used, and therefore first the resilience literature was reviewed. Resilience is often mistaken for robustness. This comparison is not correct. Robustness can be defined as: '*how difficult is it to disrupt a system'* (Nikolic & Warnier, 2021). Resilience can be defined as: '*what happens if a disruption happens, i.e. how quickly does a system recover after a disruption'* (Nikolic & Warnier, 2021). This difference is non-trivial, thus robustness and resilience should not be confused. A definition of resilience by Galbusera et al. (2018) is: '*to plan and prepare for, adsorb, respond to, and recover from disasters and adapt to new conditions'*. Bruneau et al. (2003) measure resilience in three pillars: reduce probabilities, reduced consequences and reduced time to recovery. It can thus be seen that in the literature, the definition of resilience differs. This difference mostly regards the scope of which to see the resilience, either looking at limiting the chance that a disruption happens or focussing on the recovery after the disruption has happened.

Literature studying the resilience of supply chains and networks provide insights for the Nautical Chain resilience case. Childerhouse et al. (2020) aimed to improve the resilience of a supply chain in a New Zealand log case study. This is successfully executed by building a DES model. Flexibility was found to be the most effective strategy improving the resilience in the long term. Chen et al. (2017) aimed at quantifying resilience in supply chains by constructing a measurement model, and ask for a research looking at improving the resilience. Jing et al. (2021) build a framework aimed at gaining insight in resilience of the maritime supply chains including ports. This framework focussed on multiple ports in a network structure, and resulted in the advice to identify rules and regulations mitigating the port vulnerability. Guerro et al. (2022) use complex networks to gain resilience using the COVID-19 pandemic as disruption. This led to insight in the effect of this pandemic on different kinds of ports, where the results are limited in their specificness and applicability. First, Galbusera et al. (2018) find that inventories smoothen the deepness of the shock caused by a disruption. Vanlaer et al. (2021) show that port authorities are well-positioned to increase port resilience. Kim et al. (2021) conclude that resilience had multiple factors, including collaboration, response and recovery. Abioye et al. (2021) found that a speed increase can, at least partly, help shipping companies recover their schedules after disruptions. This review on the resilience literature showed that flexibility, rules and regulations, inventories and increasing speed are possible resilience improving strategies.

2.4 Port disruptions

Verschuur et al. (2020) proposes an empirical database of past disruptions and recovery of ports. This database can then be used for model studies. For natural disruptions this research found the median of port closure to be 6 days, and a 5 day median when the port stays open. It is asked to further research combining this data with modelling approaches.

2.5 Knowledge gap

From the research regarding the Nautical Chain, a framework to construct a model regarding the Nautical Chain can be found (Verduijn, 2017). In this framework, data on the Port of Rotterdam is present. From the research of Nikghadam (2021) a focus on tugs and pilots for mitigating delays is gained, while boatmen and terminals can have less emphasis. Regarding supply chain resilience, Childerhouse et al. (2020) show that DES is a good method to look at improving the resilience, where flexibility came forward as a good mitigation strategy. Jing et al. (2021) show that rules and regulations have to be constructed to mitigate the effects of disruptions. Vanlaer et al. (2021) show that the port authority has a good position in increasing port resilience. Abioye et al. (2021) found that increasing speeds can help recovery from disruptions.

Concluding the literature review, research regarding the Nautical Chain currently did not look at resilience of this chain. Supply chain resilience did not look at individual ports or the role of the Nautical Chain. Last, critical infrastructure research did not look at the resilience of the Nautical Chain. In short, the knowledge gap in the literature is therefore the current state of resilience of the Nautical Chain, and the possibilities to improve the resilience of this chain.

From the knowledge gap presented above the research objective is identified:

To gain insight in the state of resilience of the Nautical Chain, and to gain insight in the role different actors of the Nautical Chain can play in improving this resilience.

3. System Description

In this chapter, the model development process will be elaborated upon. First the conceptual model will be presented in chapter 3.1. Next, the methodology and choice of modelling technique will be elaborated upon in Chapter 3.2.

3.1 Conceptual model

The system under study is the port Nautical Chain system, which provides services to vessels in port with piloting, towing, traffic management and mooring. Conceptualizing the system reduces the scope of the full system to a minimal system meeting the research objectives.

The organisational aim of the project is defined as:

Give insight in the current state of resilience of the Nautical Chain, and look at mitigation strategies to improve this resilience.

This organisational aim leads to the following modelling objectives:

Show the current state of resilience of the Nautical Chain and look into strategies to improve the resilience, within the Nautical Chain, depending on the kind of disruptions.

The general project objectives are summarized in table 3.1:

Table 3.1: General project objectives

Time-scale	5 months
Flexibility	Limited (only disruptions and mitigation strategies)
Run-speed	Moderate/fast: many experiments
Visual display	Limited visualisation for presentation purposes
Ease-of-use	Only by modeler

3.1.1 The Actors of the Nautical Chain

Many actors are active in ports, and to meet the modelling objectives not all actors, processes and attributes of these actors are needed. Therefore, in this subchapter it will be determined if the actor should be included in this research, and at what level of detail.

Vessel

The vessel is the main study object in this research. Since the focus is on the Nautical Chain in this research, only vessels using the services of the Nautical Chain are included in this research. Table 3.2 gives the activities of vessels and their inclusion or exclusion. Table 3.3 shows the most important attributes of vessels.

Vessel – Included	
Justification:	The vessel is the main entity in this study

Table 3.2: Activities of vessels

Activity	Include or Exclude	Justification
Sailing	Include	Moving through the harbour, speed in harbour is interesting for resilience.
At anchor due to lack of terminal space	Include	When terminals are full, vessels go to anchor, creating a queue for port entry. This is important for resilience.
At anchor for other reasons	Exclude	Other reasons, like market conditions are excluded, since this is outside the scope of the resilience of the Nautical Chain.
Boarding/deboarding pilot	Include	Key part of the Nautical Chain.
Connecting/disconnecting tugs	Include	Key part of the Nautical Chain.
Loading/unloading	Include	Takes time, unloading times can be impacted by disruptions.
Bunkering	Exclude	Outside the scope of resilience of the Nautical Chain.

Table 3.3: Most important attributes of vessels

Attribute	Unit
Destination	Terminal
Length	Meter
Class	-
Tugs Needed	Tug

Pilots

Pilots guide vessels from the ports entrance to their designated berth, and from their berth to the port entrance. Pilots are included in the model, since they can contribute to delays in port thus influencing the ports resilience. Table 3.4 shows the activities of pilots and their inclusion or exclusion.

Pilots – Included	
Justification:	Part of the Nautical Chain, possible cause for delays

Table 3.4: Activities of pilots

Activity	Include or Exclude	Justification
Idle at sea or land	Include	Idle pilots are available for vessels, and there is a limited amount of pilots. Therefore, an inventory of pilots is created when idle.
Boarding/deboarding vessel	Include	Key part of the Nautical Chain.
Transport to/from sea station	Include	The pilot vessel has limited capacity, could be reason for delays.
Transport to/from land station	Exclude	Transport on land goes often by the boatmen or taxi, which is barely a cause for delays.

Pilot vessel

The pilot vessel transports pilots from the outgoing vessel to the pilot sea rest station, and from the sea rest station to the incoming vessel. Table 3.5 shows the activities and their inclusion or exclusion in this research.

Pilot vessel – Included	
Justification:	Limited transport capacity for pilots out at sea, can cause delays

Table 3.5: Activities of pilot vessel

Activity	Include or Exclude	Justification
Picking up pilot from vessel	Include	Getting pilots to sea station, if busy the pilot has to wait possibly causing delays.
Dropping off pilot at vessel	Include	First picking up pilot at sea station, then bring it to vessel. If busy, this can cause delays.
Bringing pilots from land to sea or from sea to land	Exclude	Balancing pilots is outside the scope of this research.

Tugboat

Tugboats are a key part of the Nautical Chain. Vessels can be obliged to use towing services, thus tugs are essential for the continued operations of the port. Besides, limitations regarding tug availability influence the resilience of the port. Therefore, tugs are included in the model. However, no distinction between the different tugboat companies will be made. Table 3.6 shows what activities of tugboats are included in this research.

Tugboat – Included	
Justification:	Part of the Nautical Chain, possible cause for delays

Table 3.6: Activities of tugs

Activity	Include or Exclude	Justification
Sailing to/from vessel	Include	Calling for tugs that are far away could impact delays, thus resilience.
Shifting personnel	Exclude	There are more tugboats in port then used, thus shifts can happen without taking one tug out.
Connecting/disconnecting to vessel	Include	Takes time and all tugs have to be present.
Bunkering	Exclude	It is assumed that when a tug has to fuel up, another tug takes over due to the surplus of tugs.

Terminal

Terminals have the facilities to load and unload vessels. Terminals are also prone to disruptions. Therefore terminals are included in this model. There are however many terminals in the Port of Rotterdam. This makes the need for data very large. Therefore, the number of terminals have been reduced to 14 terminals. This reduction is based on data availability. In table 3.7 the inclusion of terminal activities is elaborated upon.

Terminal – Included	
Justification:	Part of the Nautical Chain, possible location of disruption and possible location for delays.

Table 3.7: Activities of vessels

Activity	Include or Exclude	Justification
Loading/unloading vessel	Included	Unloading takes time, and can be impacted by disruptions.
Internal terminal operations	Exclude	The internal functioning is not relevant for the scope of this research. Disruptions affecting the internal functioning of terminals will be represented by the unloading time of vessels.

Boatmen

Boatmen moor and unmoor vessels at the terminal. In the literature, it was found that boatmen are barely cause for delays in port. Therefore, boatmen are excluded from this research.

Boatmen – Excluded	
Justification:	According to the report of Nikghadam et al. (2021), boatmen are rarely cause for delays in port.

Harbour Master

The harbour master is represented by the harbour coordination centre (HCC) and the vessel traffic services (VTS) in the Nautical Chain. The literature found that the harbour master is well positioned to improve the resilience in ports. Therefore, mitigation strategies that could be enforced by the harbour master are included in this research.

Harbour Master – Partly included	
Justification:	Only for mitigation strategies, actions of the harbour master are included (policy mitigation). This results in an aggregated actor, which is only included in when some mitigation strategies are active

3.1.2 Resilience

The literature review in chapter 2 showed that definitions of resilience differed mostly in either including mitigation before the disruption occurs, thus decreasing the probability of occurrence, or only the consequences and recovery after a disruption. In this research the planning and preparing for disruptions, decreasing the probability of occurrence, is not included. This research thus only looks at mitigation after the disruption has happened, thus the consequences and recovery after a disruption, in line with Nikolic & Warnier (2021).

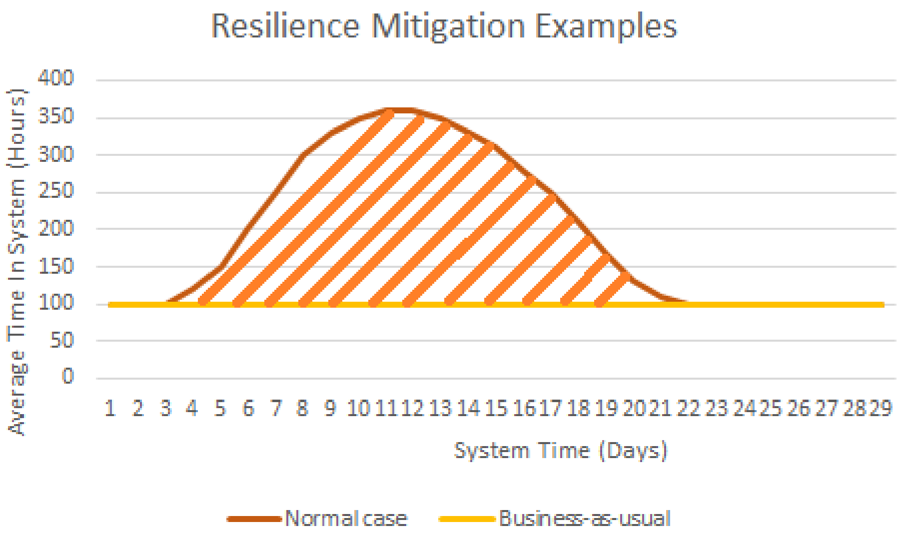


Figure 3.1: Example of normal case resilience

A disruption causes a shock in the system where in the scope of resilience, such a disruption causes the system performance to drop. After the drop in system performance, recovery has to happen. For the port system the system performance can be measured with the average time in system of cargo vessels. When the port performs normally, the average time in system will be of a certain value (100 in the example in figure 3.1). This value, under normal conditions, is called the business-as-usual value. When a disruption happens, it is very likely that the average time in system increases compared to the business-as-usual value. The area under the graph that results from the deviation of the average time in system is the measurement of resilience. This can be seen by the orange area in figure 3.1. Next, decreasing the drop in the system performance, thus increasing the resilience, compared to the base case is discussed.

The area under the graph can be influenced in two ways: (1)reducing the time to get back to the business-as-usual value which makes the area under the graph more narrow, and (2)reducing the maximum average time in system leading to a lower graph. Next, each of these area decreasing possibilities will be elaborated in more detail.

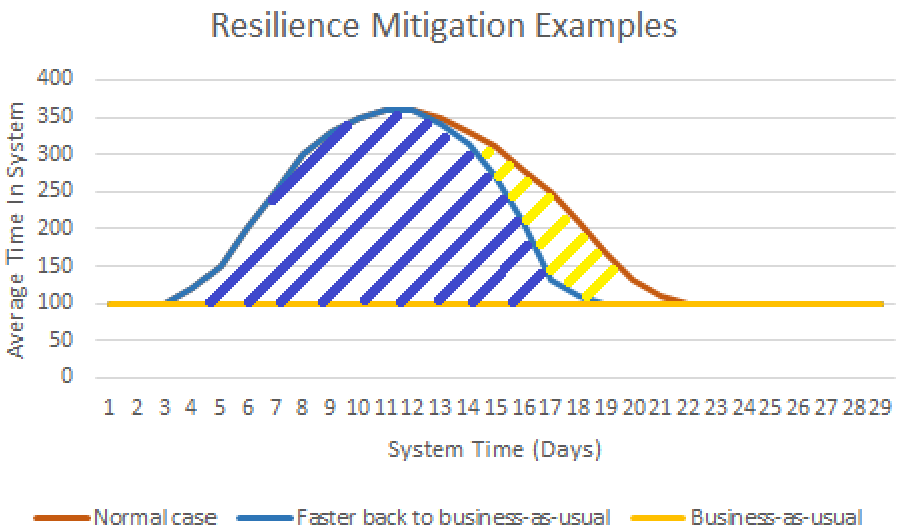


Figure 3.2: Example of getting back to the business-as-usual value sooner

First, the resilience can be measured in the time it takes to go back to the business-as-usual value. This can be seen in figure 3.2, where the orange line depicts the normal case under a disruption, and the blue line shows an improvement in the resilience by getting back to the business-as-usual value sooner. This is according to the definition of measuring resilience by Nikolic & Warnier (2021): *'How quickly does a system recover after a disruption'* or the reduced time to recovery in the triangle of Bruneau et al (2003). In this graph it can be seen that the blue area under the graph is smaller than the area in the normal case. The gain in resilience that is achieved with this effect is depicted with the yellow area.

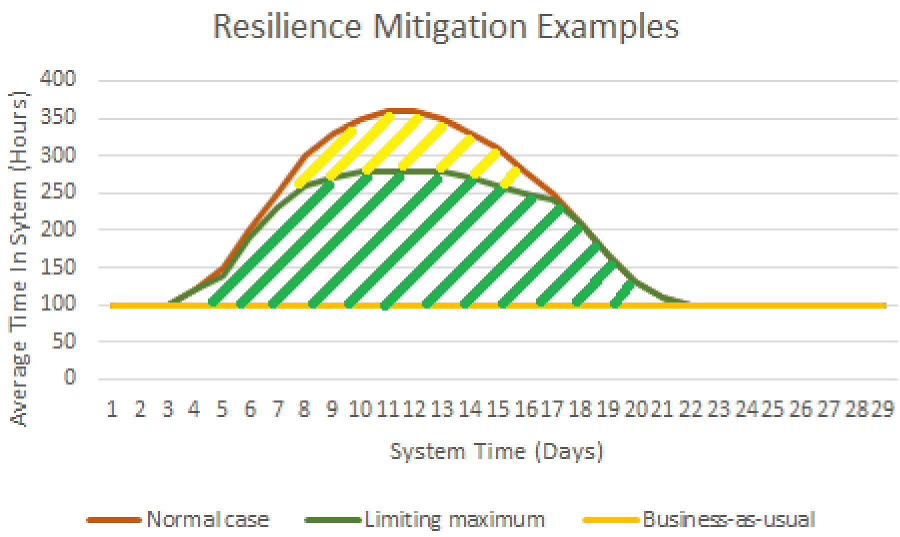


Figure 3.3: Example of limiting the maximum value on resilience

Secondly, the maximum impact on the average time in system can be reduced, which can be seen with the green line in figure 3.1. Here, the time it takes back to the business-as-usual value is the same as the normal case, but the maximum average time in system is lower than with the normal case. This is according to another definition of measuring resilience by Nikolic & Warnier (2021): *'How deep is the system performance impacted'* or reducing the consequences in the triangle of Bruneau et al (2003). The graph shows that the area is reduced compared to the normal case, where the gain in the resilience is depicted with the yellow area.

3.1.3 Disruptions

Different kinds of disruptions can happen in ports, which can be seen in figure 3.4. Among the different types of disruptions this research focusses on the most relevant for the Port of Rotterdam, namely accident, cyber-attack, pandemic, Suez Canal blockage and weather. With this set of disruptions, different impacts for the port resulted, which are:

- Accident: this simulates an event at the entrance of a branch in the port (the Maasvlakte area), which make the affected terminals unable to handle incoming vessels.
- Cyber-attack: this simulates a cyber-attack at the terminals in the Calland channel in port, making the affected terminals unable to handle vessels.
- Pandemic: this scenario simulates a three week pandemic, halving the amount of tugs and pilots during these three weeks. Also, the unloading times increase at terminals.
- Suez Canal blockage: this scenario simulates blockages at other ports or infrastructures, leading to fluctuations in vessel arrival.
- Weather: this simulates extreme weather conditions rendering the port water infrastructure unable to serve vessels, thus closing the port.

With this set of disruptions, the resilience of the port is tested on multiple different scenarios resulting in a broad scope on the resilience.

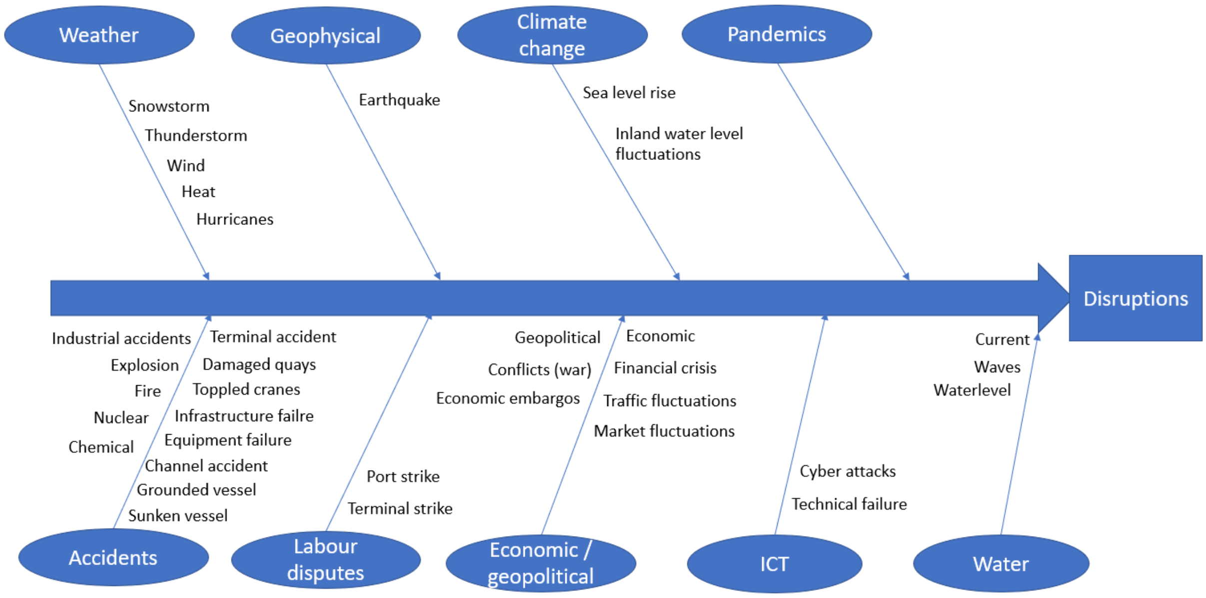


Figure 3.4: Identification of possible disruptions in ports

3.1.4 The Conceptual System

In figure 3.5, the conceptual system can be seen in a simplified diagram where the most important input and output parameters and the mitigation strategies are included. In figure 3.6 an IDEF0 diagram of the A0 level can be seen depicting the main processes of the DES model. Diagrams of the A1 level of the IDEF0 can be seen in figure 3.7 and 3.8, where the diagram is split in two to enhance the readability. In the A1 level IDEF0 diagrams the servicing of a vessel by the Nautical Chain can be seen, where the different processes included in this research can be found. Figure 3.5 shows the incoming part of the A1 level of the IDEF0, from port entry until the unloading at the terminal. Figure 3.6 shows the outgoing part of the A1 level, from finishing unloading to exiting the port. These diagrams provide a base for the construction of the DES model.

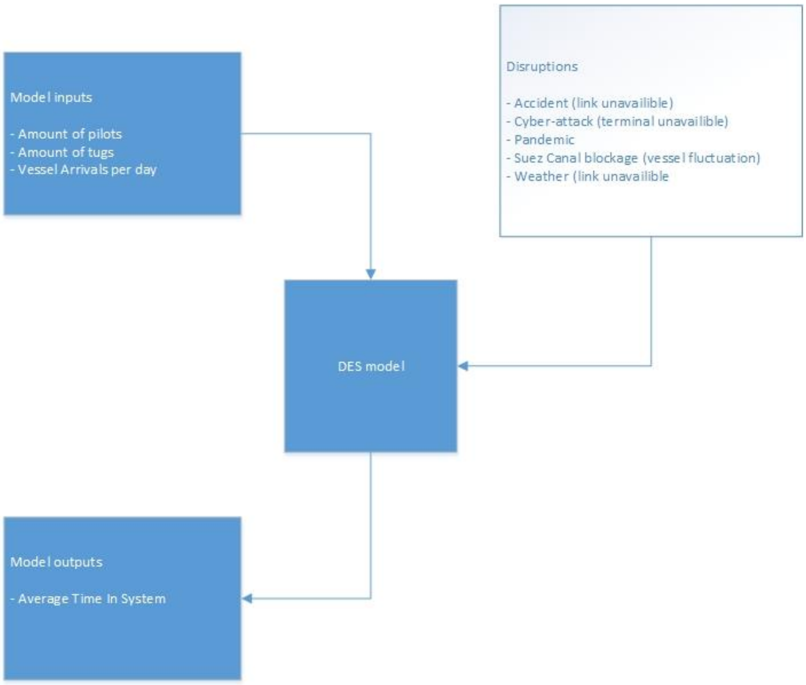


Figure 3.5: Simple conceptual model of the system

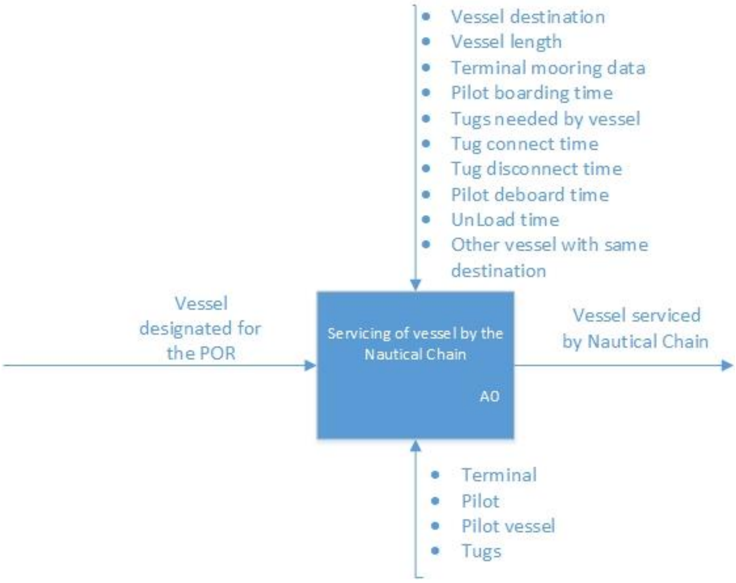


Figure 3.6: Level A0 of IDEF0

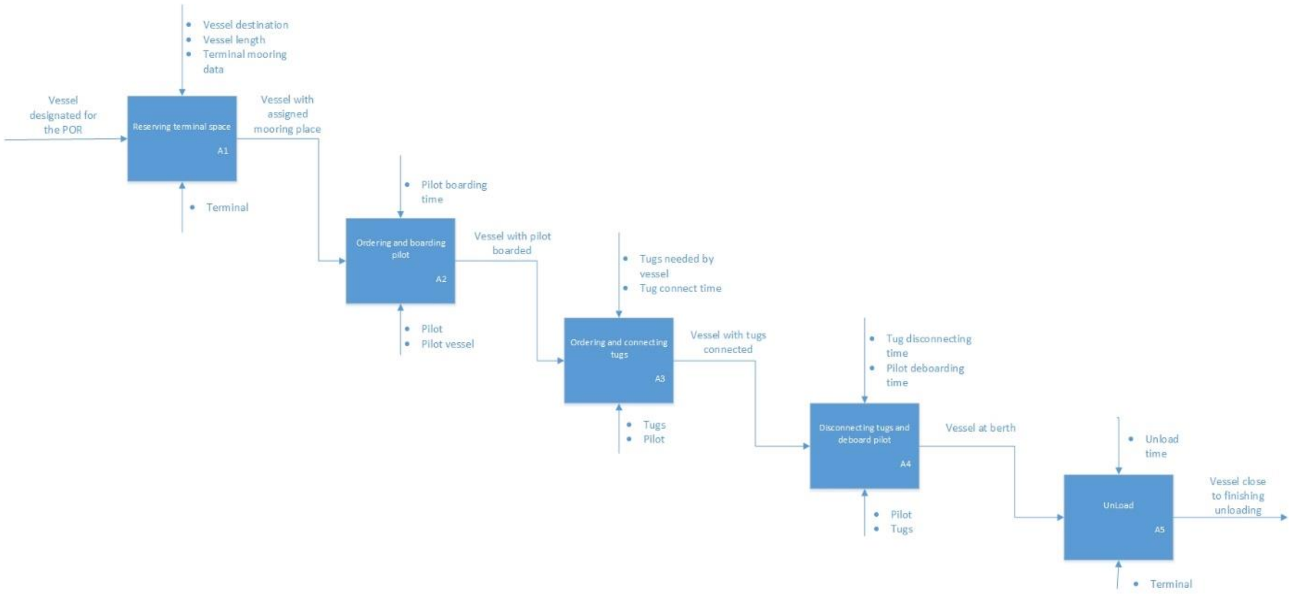


Figure 3.7: Level A1 of the IDEF0 for the incoming voyages

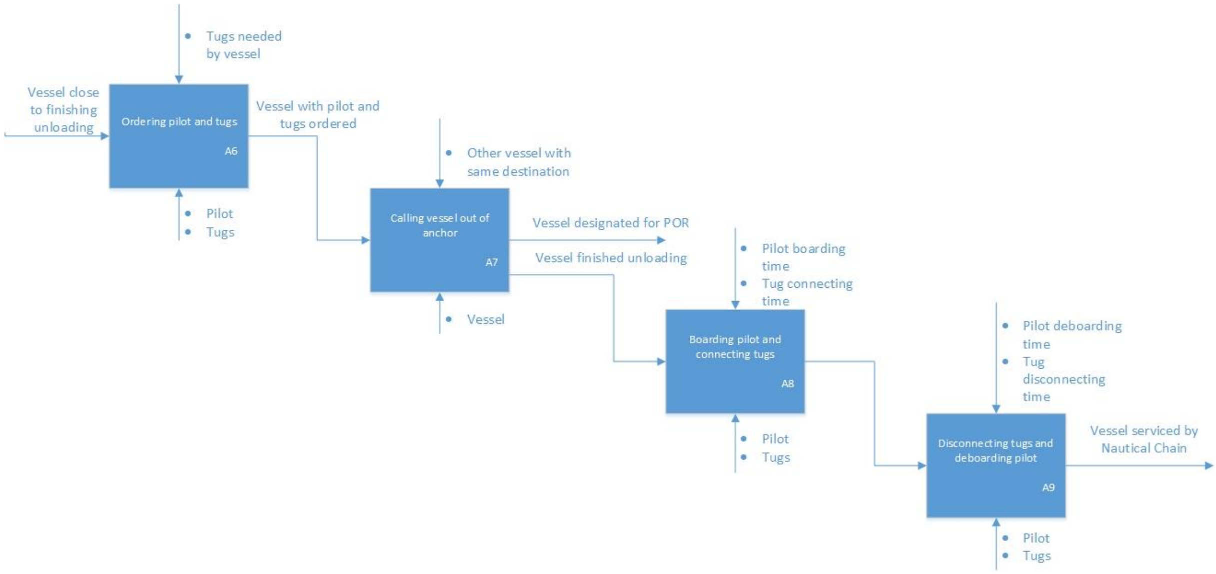


Figure 3.8: Level A1 of the IDEF0 for outgoing voyages

Average time in system

The main output variable of the system is the average time in system of vessels. Since this variable is of great importance, the methodology to gather the data for this variable is depicted in figure 3.9. The process collects the average time in system of all vessels in the system every hour, where this hourly value is saved for further analysis.

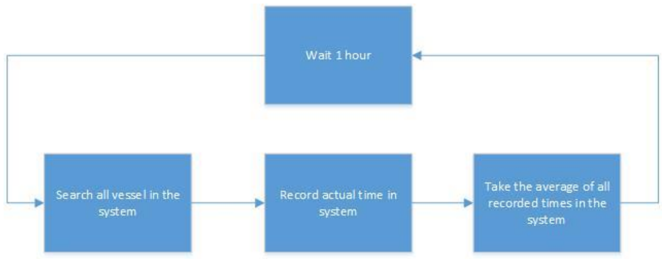


Figure 3.9: Process of gathering the average time in system output

Queues

In this system, multiple queues exists. In table 3.8 the queues and their conceptualisation can be seen.

Table 3.8: Queues in the system

Queue	Include or Exclude	Justification and explanation	Capacity and Discipline
Terminal queue	Include	When the terminal is unavailable or out of mooring capacity, vessels go to anchor. This is the terminal queue, which can be cause for delays.	Capacity: unlimited Discipline: first in first out (base case)
Pilot queue	Include	A shortage of pilots cause vessels to wait, creating the pilot queue.	Capacity: unlimited Discipline: random
Tug queue	Include	A shortage of tugs create tug queues by vessels waiting for tugs to be available.	Capacity: unlimited Discipline: random
Boatmen queue	Exclude	Boatmen are excluded from the model.	
Clearance queue	Exclude	This queue is for clearance by the harbour master to sail into port. Since the harbour master is mostly excluded, this queue can be excluded. This queue does not cause delays often.	

3.1.5 Mitigation strategies

Two classes of mitigation strategies have been identified: policy strategies and capacity strategies. For each mitigation strategy, the following rules have been used:

1. *Start the mitigation strategy on the time that the disruption has ended*
2. *The duration of mitigation strategy is twice the duration of the disruption*

Policy strategies

The policy strategies consist of four strategies, which could be enforced by the harbour master.

Increasing average speed

This mitigation strategy increases the average speed in the port with 20%. On most sections in the Port of Rotterdam there is a minimum and maximum section speed allowed, and in this research it is chosen to take the average for the vessel speeds at each section. This mitigation strategy increases the speeds on the sections with 20%, which means that the average speeds in the harbour stay below the maximum allowed speeds on the sections. However, increasing speeds in ports can lead to concerns about the safety in port. Therefore, the Vessel Traffic Centre (part of the Harbour Master) should asses the ports safety with this increase in average speed. This department has the knowledge to estimate if the speed increase is safe in the current conditions. The implementation of this strategy has to be enforced by the harbour master, which has to communicate with the pilot to sail the faster speed. This mitigation strategy shows the effect on the resilience of the Nautical Chain with this 20% increase in speeds, where the practical implementation and safety concerns have to be assessed by the vessel traffic centre and the pilots.

Vessel priority strategies

Within the policy mitigation strategy, three vessel priority mitigation strategies have been identified. These strategies were inspired by Imai et al. (2003). In this paper, a discussion was found on different vessel priority strategies, from which 3 vessel priority strategies resulted. Next, these 3 vessel priority strategies will be discussed.

Largest vessel first

The largest vessel first vessel priority strategy changes the selection for calling vessels into port, where the vessel length (in meters) is used to determine which vessel to call into port first. Vessels being at anchor are waiting for a mooring at a terminal. When a vessel leaves the berth at a terminal, the longest vessel currently at anchor designated for that terminal will be called into port. This strategy is thus implemented at terminal level, and not at the port level. The terminals and the harbour master can enforce this proposed strategy.

Less tugs first

The less tugs first vessel priority strategy changes the selection for calling vessels into port, where the amount of tugs that a vessel needs is used to determine which vessel to call into port first. Similar to the largest vessel first vessel priority strategy, this strategy is implemented at a terminal level. A vessel leaving a berth at a terminal with a queue of vessels will call the vessel into port that needs the least tugs designated for the same terminal. This can also be enforced by terminals and the harbour master.

Smallest vessel first

The smallest vessel first priority strategy also changes the selection for calling vessels into port, determined by the vessels length (in meters). This strategy is also implemented at a terminal level, where leaving vessels select the smallest vessel to be called into port when leaving. Terminals and the harbour master can enforce this strategy.

Capacity strategies

Capacity strategies are mitigation strategies impacting the resources of the Nautical Chain, where tugs and pilot capacity is increased. Increasing terminal capacity is excluded since this is not possible in the time window of the disruptions. Also, a simultaneous increase of pilots and tugs is included. These three capacity strategies will be elaborated below.

Increasing pilots

The amount of pilots is increased with 3 and 6 extra pilots, adding to the amount of pilots for the base-case. This strategy can only be implemented by the pilot organisation in port. When during a disruption the throughput of the harbour is decreased, less pilots are needed which creates the possibility to add extra pilots after the disruption has ended. The two levels of pilot increase provides insights in the effect of adding extra pilots, and the improvement that can be made with each individual added pilot.

Increasing tugs

The amount of tugs is increased with 2 and 5 extra tugs, adding to the amount of tugs for the base-case. This strategy can only be implemented by the tugboat companies. As with the pilots, the amount of tugs needed in port might be less during a disruption, creating the possibility to use these tugs when the disruption has ended. It has been chosen to also increase the amount of tugs in two levels, which provides insight in the contribution to improving the resilience for each added tug.

Increasing both pilots and tugs

With this mitigation strategy, the amount of pilots is increased with 6 extra pilots and the amount of tugs is increased with 5 extra tugs simultaneously, both adding to the amounts for the base-case. Both the pilot organisation and the tugboat companies have to enforce this strategy, asking for collaboration between these organisations. With this mitigation strategy insight can be gained in the effect of a simultaneous increase, and if this effect is larger than the sum of only increasing with 6 pilots and only increasing with 5 tugs.

3.1.6 Assumptions and simplifications

With the conceptualisation of the Nautical Chain system to a reduced system, assumptions and simplifications were made. In this sub-chapter the main assumptions and simplifications will be discussed. Appendix A presents the assumptions and simplifications in more detail.

Assumptions

The most important assumptions made in this conceptualisation can be seen in table 3.9. The assumptions presented resulted from a lack of (specific) data.

Table 3.9: Most important assumptions in the model

Assumption	Justification
The speed of the section is the average between the minimum speed and maximum speed	No data on actual speeds, so it is assumed that it is the average between minimum and maximum. This will be calibrated in chapter 5.
Assumptions on length data	The vessel lengths are in a range with minimum and maximum values. It has been chosen to use a continuous random distribution.
Assumptions on unload time data	The data on the unload times of vessels was not complete for all terminals. Therefore, it has been chosen to take the value of the next class with an unload time, starting with the higher class.
Assumptions on terminal data	Data on terminals is limited. The vessel arrivals are based on a section, and one section can have multiple terminals. Since no data on mooring was present, an estimate had to be made by using google earth. For terminals on the same section the mooring capacity has been summed.

Simplifications

The simplifications made in this research can be found in table 3.10. Simplifications are made to be able to model the system within the time window of this research.

Table 3.10: Most important simplifications

Simplification	Justification
Only sea going vessels designated for the Port of Rotterdam included	In this research, only vessels that require the services of the Nautical Chain are included. Vessels not designated to the Port of Rotterdam have a terminal at a different port, and are therefore outside the scope of this research.
Only vessels that require piloting included	Only vessel requiring services from the Nautical Chain are included. All other vessels are outside the scope of this research.
Boatmen not included	According to literature (Nikghadam et al., 2021), boatmen are barely cause for delays in ports.
Encountering and overtaking rules not in cooperated	The available time for this research required this simplification to be made.
There are no different tug companies	Lack of data on the different shipping companies and which towing service they use. Also arrival data does not incorporate the different vessel companies, and it does not contain the amount of vessels for each different shipping company.
Terminals are grouped together, and vessels can go to all mooring places in this terminal	The available data had arrival data on sections, not terminals. Some sections have multiple terminals. Therefore, these terminals and their resources are grouped together.

3.2 Discrete event simulation and Simio

The objective of this research is to give a quantitative answer on the state of resilience of the Nautical Chain, and quantitatively answer the effects of the different mitigation strategies on the resilience of this chain. In the literature simulation modelling has successfully been implemented for the port system, like Fransen et al (2021) and Childerhouse et al. (2020). Therefore, three different simulation modelling techniques will be discussed for use in this research.

3.1.2 Choice of modelling technique

For the simulation modelling of the resilience of the Nautical Chain, agent-based modelling (ABM), continuous simulation and discrete event simulation (DES) have been considered. ABM is known to have the application to give insight in how different autonomous entities interact in systems. In the previous SWARMPORT research, ABM has been chosen as modelling technique. The focus of this project was to see how information sharing between the actors of the nautical chain can benefit the efficiency of the port. The interactions between the agents in the model is important, leading to ABM as a good method. For this research however, the main focus is on system performance, and interactions between the different actors is not included. Therefore, ABM is not the best method to study the resilience of the Port of Rotterdam with regard to the nautical chain. Continuous modelling (system dynamic modelling) is also considered for this research. This modelling technique is well known to model stocks and flows, where the simulation is continuous. For the purpose of modelling the Nautical Chain in the Port of Rotterdam, this technique has disadvantages. The flow of vessels in the Nautical Chain is not continuous. The required differential equations are hard to define for this research, and if found, these equations will not represent the actual situation of the Nautical Chain. This is due to the balance the differential equation strives for. Also, the resources of the different actors are hard to define in a system dynamic model. This makes system dynamics not the best method to research the resilience in the Port of Rotterdam with regard to the Nautical Chain. However, the Nautical Chain in this port can be seen as a queuing system, where different organisations of the Nautical Chain are service stations and sequencing of the tasks is needed. These kind of systems are very well suited to be modelled by Discrete Event Simulation (DES). DES is primarily known for modelling queuing systems with servers, resources and links. The main purpose of DES is to give insight on how items move through a system. This aim of DES is very close to the actual situation of the nautical chain in the scope of this research, with the items being vessels serviced by the organisations of the nautical chain. Therefore, DES is chosen as simulation modelling method for this research.

3.2.2 Software package

To simulate the port system in an discrete event model, the Simio software package will be used. This simulation tool is an elaborate and easy working software package intended to use for discrete event simulation.

4. The Simulation Model

Table 4.1 provides an overview of the model entities, inputs, outputs and main assumptions.

Table 4.1: Model overview

Entities in the model	Vessel, pilot, pilot vessel, tug, terminal
Model inputs	Number of tugs, number of pilots, section speed factor, vessel arrival factor, unload factor, tugs needed factor, run length, tug processing time, pilot processing time
Main model outputs	Average time in system (throughput time), average time waiting for pilot, average time waiting for tug, average time waiting for room at terminal, occupancy of pilots, occupancy of tugs, occupancy of terminals
Main model assumptions/simplifications	No boatmen Certain terminals together Only sea-going vessels designated for the POR Always pilotage needed No encounter and overtake rules

This chapter will show the main logic of key processes of the model relative to the executing entity. Since the vessel is the most important entity in the model, this chapter starts with the explanation of the vessels processes. Next, the pilot processes will be discussed, and last the tug processes will be discussed.

4.1 Cargo Vessel

First, the process from the point of view of a cargo vessel entering the port will be discussed. This will start with the generation and assigning values. Next, reserving terminal space, pilot processes, tug processes and terminal processes will be discussed. In Figure 4.1 the general overview of the process of a vessel is given going through the harbour. Each of these sub-chapters contains the basic information about how the model works.

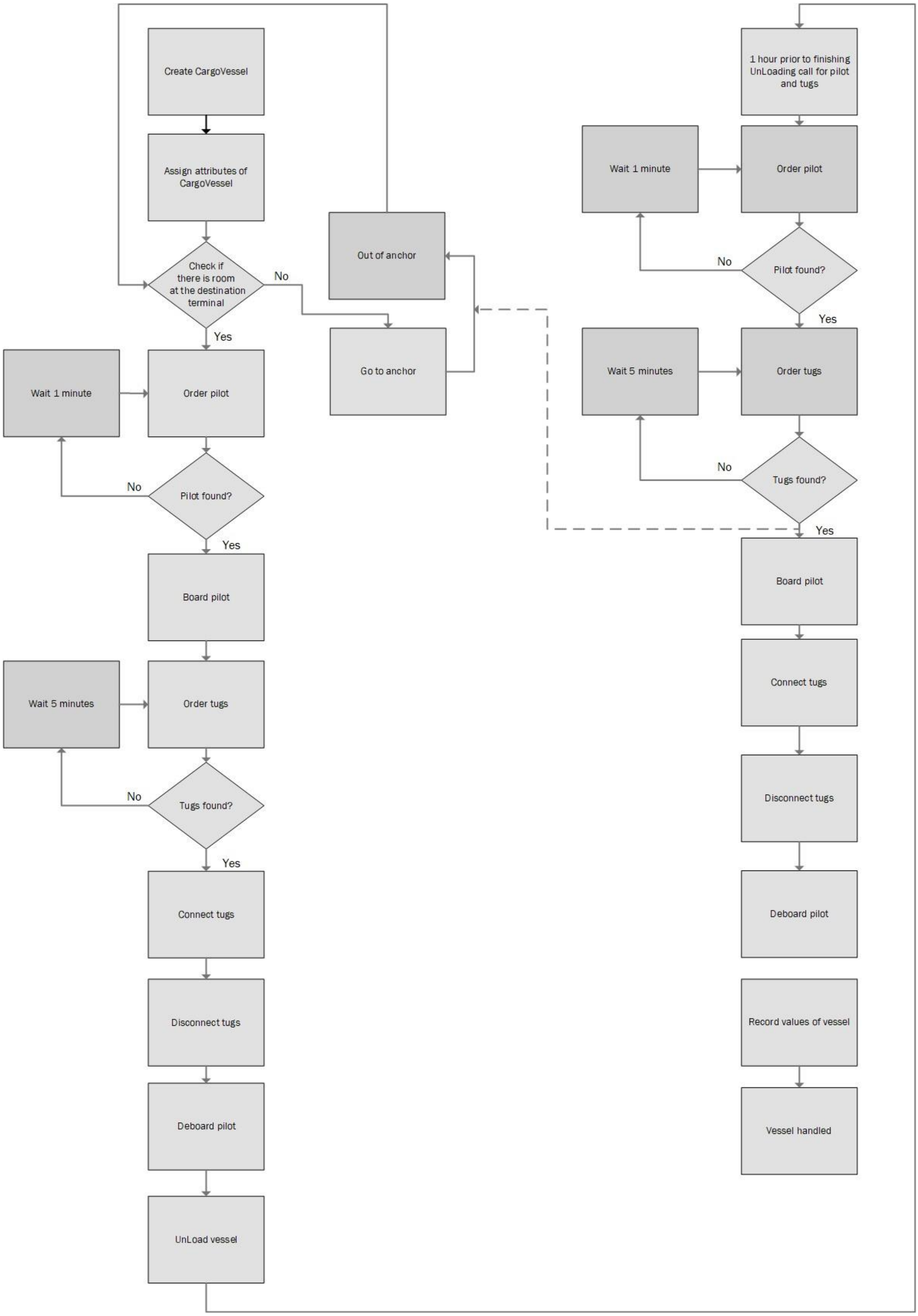


Figure 4.1: Process of vessel trough the model

Generating cargo vessel and assigning values

From the data of Verduijn (2017), all values for assigning the variables of the vessel are gathered. After the vessel is generated, the vessel will assign the values. These values have to be set in a specific order, since some assignments depend on previously set values. The order can be seen in Figure 4.2.

The Class of the vessels is in range [1, 2, 3a, 3b, 4, 5, 6]. For modelling purposes, the classes 3a and 3b have been called 31 and 32 respectively. From now onwards, these classes will be called as such. After the class of the vessel is set, the destination can be set. Not all classes go to all destinations, and therefore the class must be assigned first. Next, the length will be set, which is also dependent on the vessel class. Thereafter, the amount of tugs the vessel needs will be set, which is dependent on the class. The amount of tugs a vessel needs ranges between 0 and 4. Last, the unload time will be assigned, which is dependent on both the class and destination of the vessel.

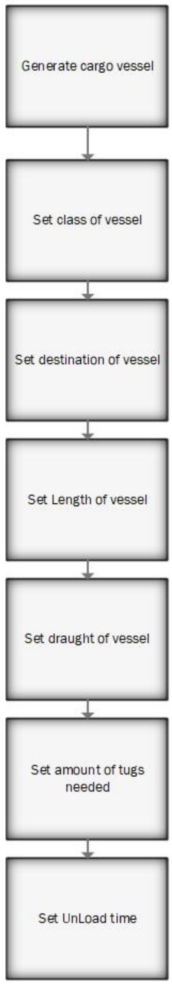


Figure 4.2: Assigning values

Reserving terminal space

After the variables of the vessel have been assigned, the vessel sails towards the harbour. Here, the vessel will try to reserve the required space at the destination terminal. A schematic simplified overview of this process can be seen in Figure 4.3, where it can be seen that the vessel can either have a destination terminal with a quay length or a terminal with a fixed amount of mooring places. When terminals have a length, which are mostly container terminals, the vessel assesses if it still fits in the remaining length at the terminal. The vessel increases its length with 10%, since mooring lines take up room. If the vessel fits in the remaining space, the vessel will go towards the terminal, and if not it will go to anchor. For terminals with mooring places, the vessel just looks if there is a free mooring place. If there is a free mooring place, the vessel will continue to the terminal, if not, the vessel will go to anchor.

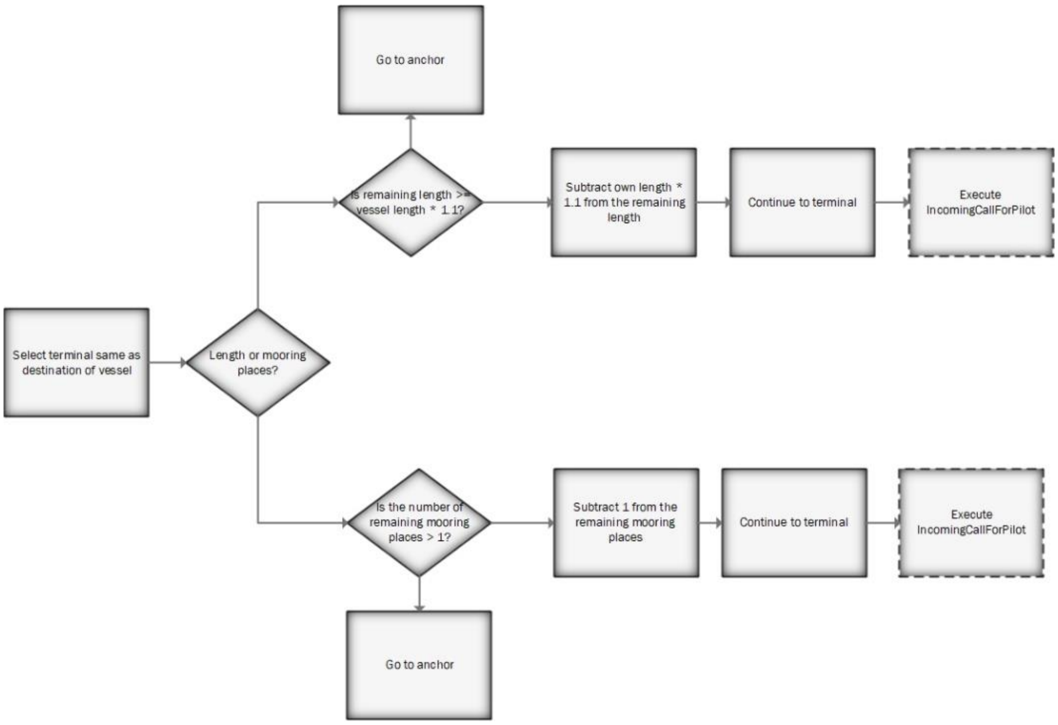


Figure 4.3: Reserving space at a terminal

Vessel and pilot

After the vessel has reserved a space at the terminal, it will call for a pilot at the pilot sea boarding station. This is modelled by a combiner, where the vessel will enter the parent input of the combiner. The simplified process of calling a pilot is shown in Figure 4.4.

This figure shows that if no pilot is found, the vessel will try again every minute. During this waiting time, the vessel will stay out at sea. When the pilot is found, the vessel will continue sailing to the boarding station. Upon arrival at the boarding station, once both the pilot and vessel are present, the pilot and vessel will be batched which takes the pilot processing time. Both the pilot and the vessel know who to batch with, so only the called pilot can be batched with the vessel and vice versa.

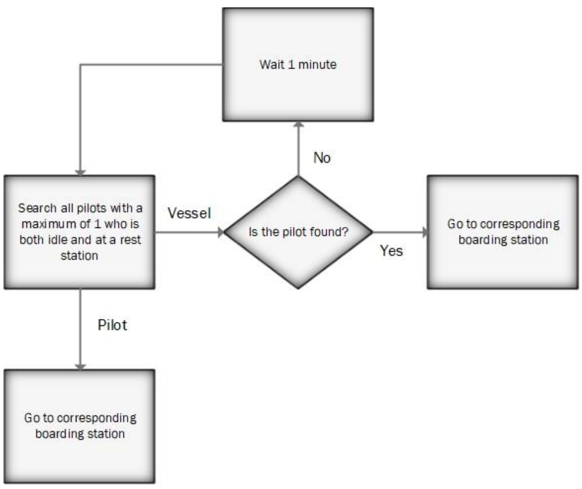


Figure 4.4: Calling for a pilot

Vessel and tugs

Once the pilot has boarded the vessel, the tugs are ordered. A simplified representation of this process can be found in Figure 4.5 It has to be noted that not all vessels need tugs. These vessels still run the process, but search for 0 tugs, thus continue to the tug connect station without any tug ordered.

For the vessels that need tugs, first the vessel searches for the right amount of tugs. Next, it checks if it found all the tugs it needs. If it has not found the right amount of tugs, but it found some, the new search will be for the amount of tugs it needs – the amount of tugs it already found. The vessel will wait 5 minutes before searching again. When the vessel has found the right amount of tugs, it will continue to the tug rendezvous location.

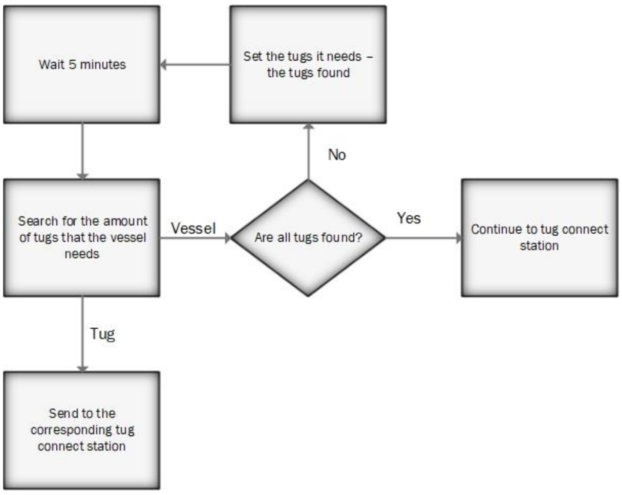


Figure 4.5: Calling for tugs

The rendezvous location is a combiner in the model. Upon arrival at the rendezvous location, the vessel will enter the parent input of this combiner. Once all tugs are present, the tugs and vessel will be batched. This will take the tug processing time. It has to be noted that the tugs know which vessel called them, and in the combiner only the tugs that are called by the specific vessel can be batched.

Vessel terminal operations

The terminal operations of the vessel start when the tugs are disconnected and the pilot has deboarded. The vessel then parks at the terminal node, where the unload process begins. This is a very complex process, for which a detailed explanation can be found in Appendix A. The simplified process can be seen in Figure 4.6, and will be discussed here.

The vessel is not doing anything until it is one hour prior to the unloading time. At this time, the vessel will start calling for a pilot, which is a process similar to calling a pilot for incoming vessels. After the pilot has been found, the vessel will search for tugs. This process has similarities with the process described for incoming voyages. After all tugs are found that the vessel needs, the vessel will free up the space it took at the terminal.

Next, the vessel will find a vessel at anchor with the same terminal as destination, and ask it to unpark. Since the space has already been freed, this vessel could take this space and start sailing into harbour, as long as the free space is sufficient for that vessel. After that, the vessel will wait another hour to finish the unloading, unpark, and continue to the pilot boarding station of that terminal.

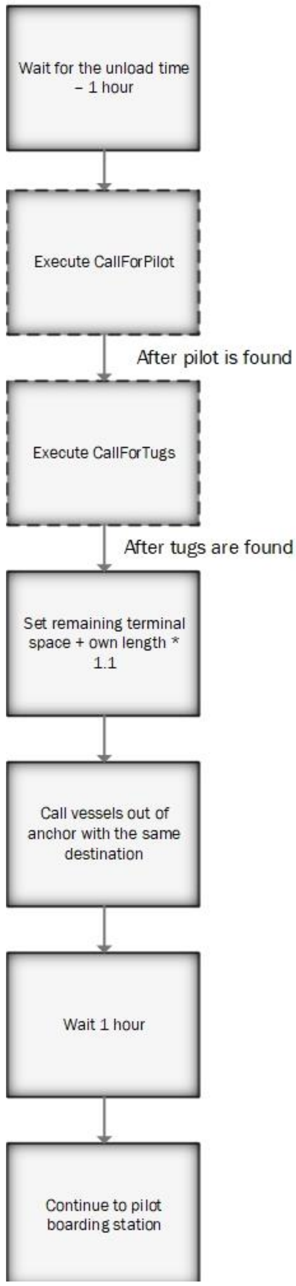


Figure 4.6: Terminal operations

From terminal to port exit

Upon arrival at the pilot boarding station of the terminal, the pilot will board the vessel which takes the pilot processing time. After the pilot has boarded, the vessel will continue to the tug connect station of the terminal. Here, the tugs will be connected, which takes the tug processing time. Next, the vessel with the pilot and tugs will head to the tug disconnecting separator close to the port entrance.

At this separator, the tugs will be disconnected which takes the tug processing time. The vessel leaves the separator at the parent output and heads to the pilot deboarding separator in the pilot deboarding area. Once arrived, the pilot will deboard which takes the pilot processing time. The vessel will exit the separator at the parent output, after which it will head towards the sink at sea. Before entering this sink, the vessel will record output values, after which the vessel is out of the scope of the model.

4.2 Pilots

In this sub-chapter, the processes that a pilot executres will be discussed. A simplified overview of the pilot processes can be found in Figure 4.7. First, the pilot generation will be discussed, after which the idle, boarding and deboarding behaviour will be discussed.

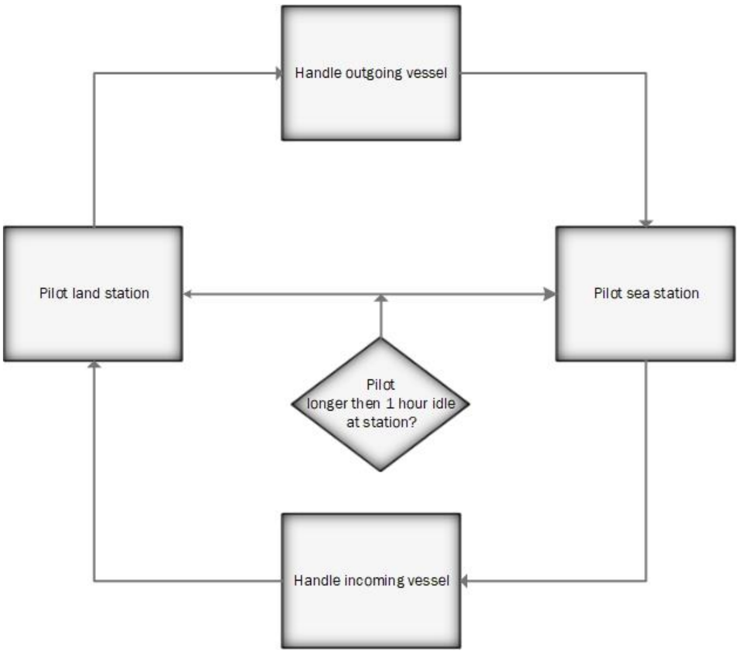


Figure 4.7: Pilot processes

Pilot generation

From the model parameter NumberOfPilots, the amount of pilots to create is determined. All generated pilots are send to the pilot land station, where first it will be checked if the pilot has an assignment. If the pilot has no assignment, the pilot will be parked at the land station.

Pilot idle behaviour

When the pilot is at either the land or sea station, every minute it is checked if the pilot is parked at this node for longer than one hour. If the pilot has been parked longer than one hour, it will be send to the other station. This holds for both the land station and the sea station. This is done to balance the pilots, mostly due to the start-up state of the model. When the model starts, there are no vessels in the harbour. Therefore, all pilots should be at sea. After handling a vessel, without the balancing, the pilot will remain in the land station until it is assigned to an outgoing vessel. This means that there can never be more vessels in the harbour at the same time as there are pilots, which is unrealistic. Therefore, there has been chosen to balance the pilots if they are idle at a station for more than an hour.

Pilot boarding behaviour

Incoming voyages

For incoming voyages, the vessel looks for an idle pilot which is currently at the pilot sea station. The vessel can call the pilot to get to the pilot boarding station at sea, which is done in the IncomingCallForPilot process. When the pilot is selected it sets its destination to the member input of the pilot boarding combiner, sets the idle variable false and unparks. From the rest station, it will go to the pickup node where it will be picked up by the pilot vessel. Upon arriving at this node, it will make a call for the pilot vessel, which adds the pickup of the pilot to the pickup queue. When picked up, the pilot vessel will bring the pilot to the boarding station. When both the pilot and the vessel are present at the pilot boarding combiner, the pilot will board the vessel, which will take 10 minutes.

Outgoing voyages

When an outgoing vessel calls for a pilot, it searches for pilots who are idle at the land station. When the pilot has been found it will set the node for the boarding station of the terminal where the vessel is calling from, set the idle variable false and unpark from the land station. From there, it will go directly, not via the water infrastructure network, to the member input of the boarding station. When both the vessel and pilot are present, the pilot will board the vessel which takes 10 minutes. An exemption to this process occurs when the vessel cannot find the tugs it needs within one hour. If the vessel did not find (enough) tugs, the pilot will leave after an hour, and the vessel has to find a new pilot.

Pilot deboarding behaviour

Incoming voyages

When the vessel arrives at the terminal, first the tugs will be disconnected. After disconnecting the tugs, the pilot will deboard the vessel, which takes the pilot processing time and is done by a separator. The pilot will exit the separator at the member output, from where it will set the pilot land station as destination. Upon entry, the idle variable is set to true as well. Upon arriving at the land station, the pilot will park, and only then can be called for a new assignment. This simulates the shift change of pilots.

Outgoing voyages

For outgoing voyages, the pilot will deboard the vessel at the pilot deboarding separator at sea. The deboarding of the pilot will take 10 minutes. After this process, the pilot will exit the member output of the separator, where it will immediately call for a pilot vessel to pick him up and set the idle parameter to true. The destination of the pilot will be set to the pilot sea station. Upon arrival of the pilot vessel, the pilot boards the pilot vessel and the pilot vessel will sail the pilot to the pilot drop off sea node. When the vessel arrives here, the pilot will deboard the pilot vessel and the pilot will park at the sea station. Only when the pilot is parked here, it can get a new assignment.

Pilot vessel

The pilot vessel has been implemented as a vehicle entity in Simio, already creating several useful properties for the vessel. A vehicle in Simio has the capability to be seized and released, travel between locations, and to act as a transporter that can pick up, carry, and drop off entities. When a pilot is either at the pilot deboarding station at sea or is called for a pickup by a vessel, the pilot will either go to or be at a transfer node.

At this node, the pilot cannot travel any further without the pilot vessel. Once arriving at this node, it will make a visit request for the pilot vessel. The pilot vessel in turn responds by placing this request in a queue, where the strategy is first in first out. When there are multiple pilots at a certain location however, the vessel will pick up all these pilots (if capacity allows), even if the other pilots are later in the queue. These requests will then be removed from the queue. Due to the fact that after pickup, the next destination is always the drop-off of the pilots on board, it does not matter for the drop-off queue.

When the pilot vessel is idle, and has no request to handle, it will go to a transfer node positioned between the boarding and deboarding stations so that it can quickly respond to any request.

4.3 Tugs

The simplified tug process can be seen in Figure 4.8. First the tug generation process will be discussed, next the tug idle behaviour, tug connect behaviour and last the tug disconnect behaviour.

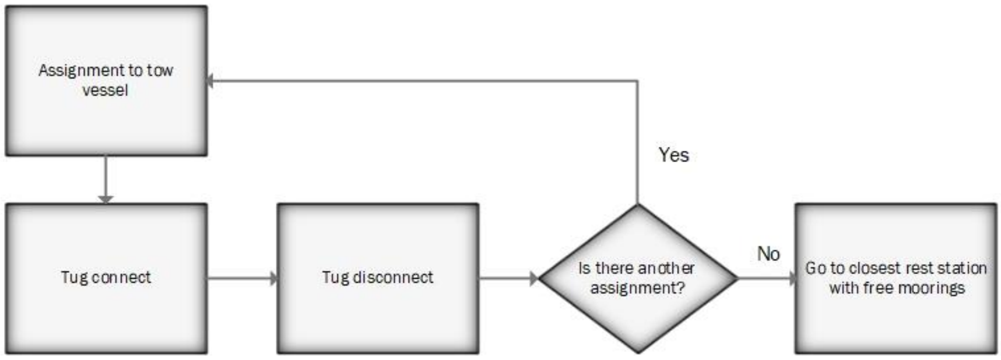


Figure 4.8: Tug process

Tug generation

From the model parameter NumberOfTugs the amount of tugs to create will be determined. After generation, the tugs will start sailing into the harbour, where they will look for an assignment. If there is no assignment yet, the tug will show the tug idle behaviour, which will be explained next.

Tug idle behaviour

When a tug has no assignment, the tug goes to a rest station. There are 4 tug rest stations in the Port of Rotterdam where the tug can choose from. All these rest locations have a limited mooring capacity. The rule the tug uses when searching for a rest station is: find the closest rest station with free moorings. When found, the rest station will decrease the free moorings with one, and the tug will set that rest location as destination. Once arrived, the tug will park until a new assignment selects the tug. It will then unpark, and increase the free moorings with one.

Tug connecting behaviour

Incoming voyages

When a tug is selected by a vessel for towage, the tug will set the idle parameter to false. There are three tug rendezvous location in port, and the rendezvous location is depending on the destination terminal of the vessel. The tug will sail to the rendezvous location corresponding with the destination of the vessel, and the tug will remember which vessel it has to tow. Once arrived at the tug rendezvous location, modelled with a combiner, the tug will enter the member input of the combiner. Meanwhile, the vessel will enter the parent input of the combiner. Once all tugs that the vessel needs are present and the vessel is present, the batching will start which takes the tug processing time. After the batching, the tugs will sail with the vessel towards the terminal.

Outgoing voyages

The process for the outgoing voyages is very similar to the process of the incoming voyage. The only difference is that now the tug rendezvous location is at the terminal.

Tug disconnecting behaviour

The disconnection of tugs is modelled with a separator. Here, once the vessel with connected tugs arrives at the terminal, the separator will split the batch, which takes the tug processing time again. The tugs will exit the separator at the member output, and the vessel at the parent output. The tug will set the idle parameter to true, which means it can be assigned to a new vessel. Unless the tug immediately gets assigned a new vessel, the tug will execute the idle behaviour and head towards the closest rest location with free moorings.

5. Data

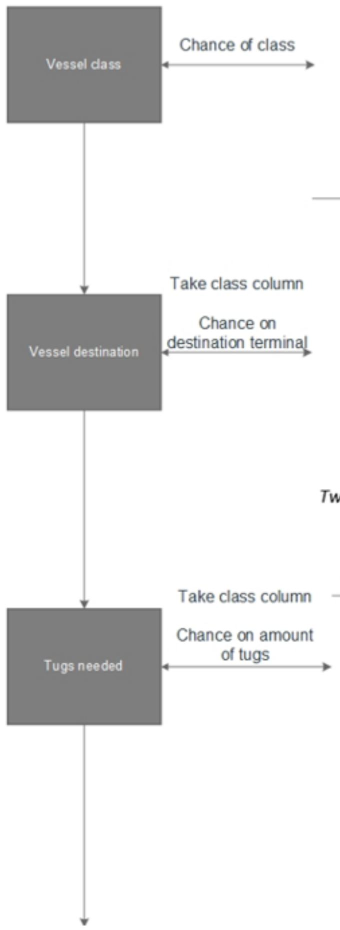
Now that the model has been constructed, the input data of the model have to be implemented. After implementation of this data, calibration, verification and validation are performed.

5.1 Input data

To run the model, data is needed. The main data used to run the model is given in this chapter, starting with vessel data followed by pilot data, tug data, and terminal data. Only the main data is discussed in this chapter. For aggregation methods and more data see Appendix B.

5.1.1 Vessel Data

First, the daily amount of vessel arrivals retrieved from the data of Verduijn (2017), and within the scope of this research resulted in 42 vessel arrivals per day. Besides, the values of attributes of vessels have to be set. Some values of the these attributes are depending on previous assignments, which means there is a fixed order of assigning the vessel values. The most important vessel values and the order of assigning them can be seen in Figure 5.1. In this figure, the data values are also given. This data is aggregated from data of the thesis of Verduijn (2017). The original data and aggregation methods can be found in Appendix B.



Class	%
1	36,61
2	43,14
31	14,33
32	1,86
4	3,22
5	0,44
6	0,40

Terminal	% Class 1	% Class 2	% Class 31	% Class 32	% Class 4	% Class 5	% Class 6
Calland	33,91	51,49	43,82	47,13	3,92	4,76	57,89
MOT	0,70	0,09	4,72	14,94	0,65	0,00	42,11
Petroleum6	1,22	2,47	1,35	5,75	0,00	0,00	0,00
ECTAmazone	2,61	9,45	9,89	24,14	31,37	23,81	0,00
EMOMissisippi	2,61	0,17	0,22	1,15	0,00	0,00	0,00
ECTEurope	3,13	3,15	19,33	0,00	13,73	0,00	0,00
APM	2,43	4,68	7,42	0,00	13,73	4,76	0,00
Euromaxx	2,09	6,30	0,00	0,00	16,34	23,81	0,00
MW	0,00	0,26	1,35	5,75	0,00	0,00	0,00
RWGAPMT	1,57	6,04	9,89	1,15	20,26	42,86	0,00
Petroleum3_1	9,57	3,91	0,22	0,00	0,00	0,00	0,00
Petroleum3_2	9,74	3,91	0,00	0,00	0,00	0,00	0,00
TweedeWerkhaven	8,52	2,81	0,90	0,00	0,00	0,00	0,00
Botlek	21,91	5,28	0,90	0,00	0,00	0,00	0,00

Tugs needed	% Class 1	% Class 2	% Class 31	% Class 32	% Class 4	% Class 5	% Class 6
0	94,40	69,56	45,55	2,25	17,53	13,04	0,00
1	4,00	12,04	13,58	2,25	5,84	0,00	0,00
2	1,54	18,25	38,39	35,96	64,94	65,22	0,00
3	0,06	0,05	1,90	58,43	11,04	21,74	10,53
4	0,00	0,10	0,58	1,12	0,65	0,00	89,47

Figure 5.1: Assigning attributes of vessels

5.1.2 Pilot Data

Pilot data mainly consist of the pilot boarding locations at port entry. The region where the pilot boards for incoming voyages is the orange region in Figure 5.2. Pilot deboarding for outgoing voyages also takes place in this region.

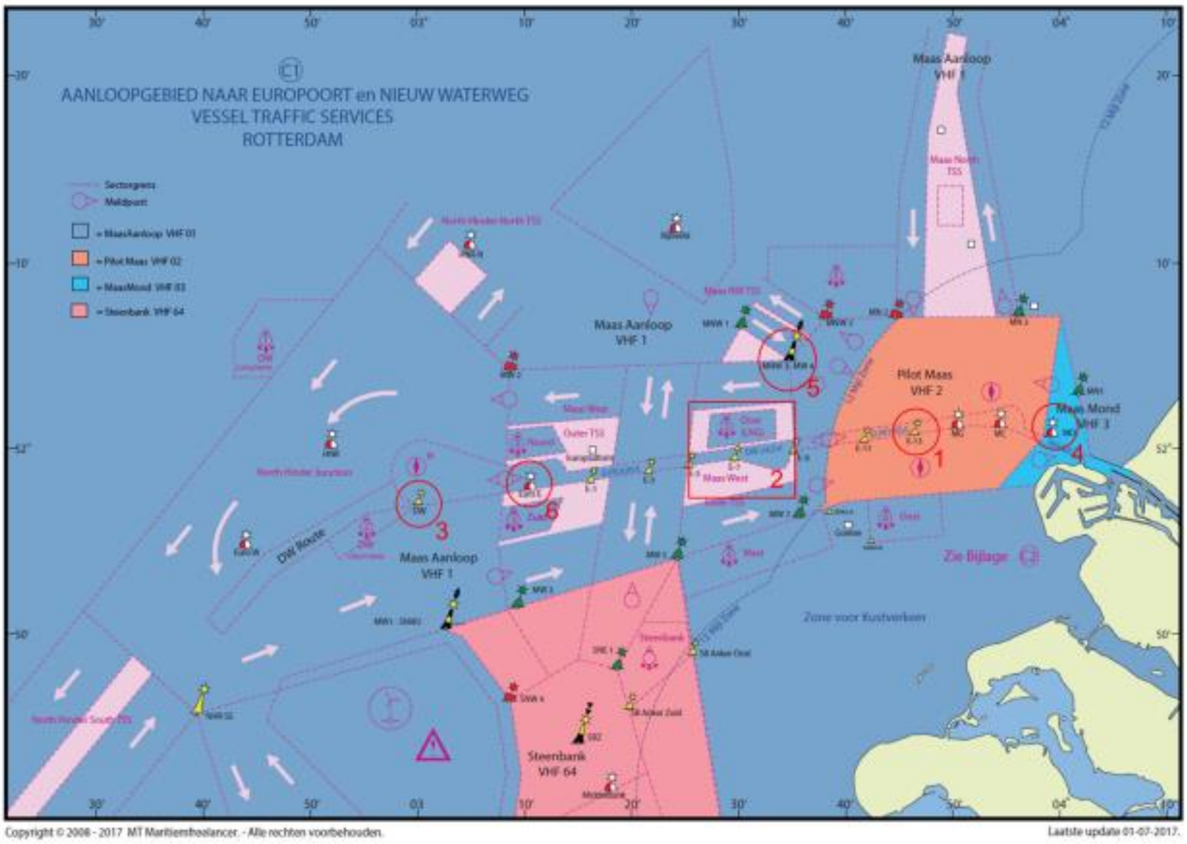


Figure 5.2: Pilot boarding areas

5.1.3 Tug Data

Data regarding the tugs mainly consists of the tug rest locations and the tug rendezvous locations. The tug rest locations are the mooring facilities for idle tugs, thus tugs without any assignment. There are four tug rest locations in the harbour, with a limited amount of mooring places.

Depending on the destination of the vessel, three different tug rendezvous locations are used within the scope of this research. The tug rendezvous locations and their corresponding destinations can be seen in Table 5.2.

Table 5.2: Tug rendezvous locations and vessel destinations

Tug rendezvous location name	*Vessel destination*
Maasvlakte	MW
	RWGAPMT
	Euromaxx
	MOT
	Petroleum6
	APM
	ECTEurope
	ECTAmazone
	EMOMissisippi
Calland	Calland
Maas	TweedeWerkhaven
	Botlek
	Petroleum3_1
	Petroleum3_2

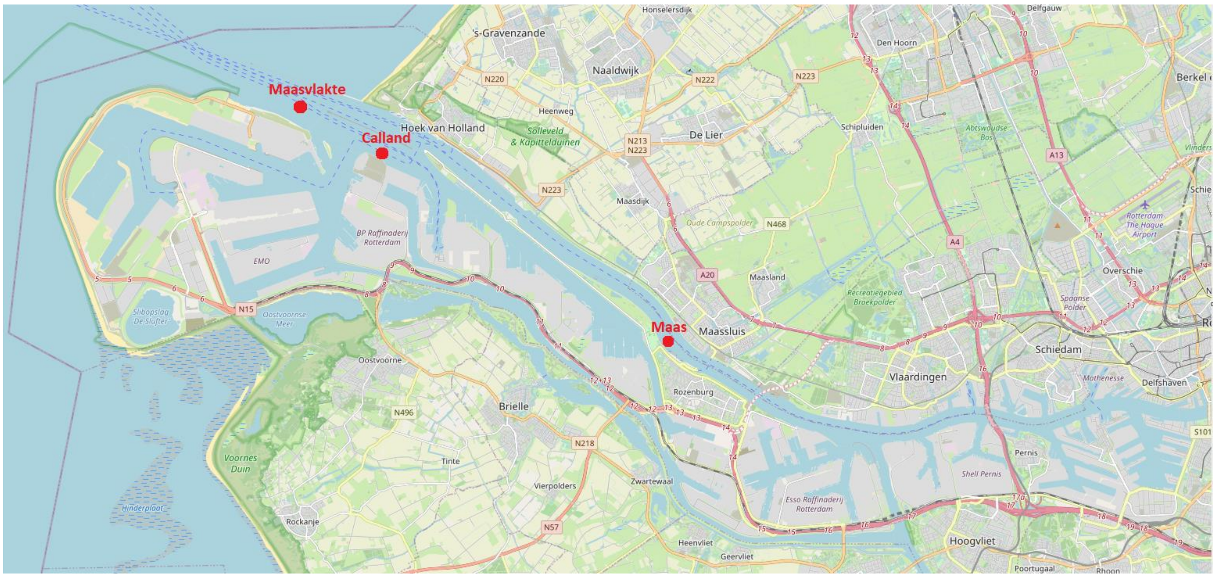


Figure 5.2: Tug rendezvous locations in port

5.1.4 Terminal Data

The terminal data mainly consists of the mooring capacity of the included terminals. This mooring capacity can be a fixed amount of mooring places, often seen with chemical and oil terminals, or a quay length often seen with bulk and container terminals. Depending on the terminal, either the amount of mooring locations or the amount of quay length is determined, for which the value can be found in Table 5.3.

Table 5.3: Quay data of terminals

Terminal	*Mooring places or Length*	*Places or length*
Calland	Mooring places	62
MOT	Mooring places	4
Petroleum6	Mooring places	9
ECTAmazone	Length	2000
EMOMissisippi	Length	1800
ECTEurope	Length	1000
APM	Length	1000
Euromaxx	Length	1400
MW	Mooring places	4
RWGAPMT	Length	2200
Petroleum3_1	Mooring places	11
Petroleum3_2	Mooring places	11
TweedeWerkhaven	Mooring places	15
Botlek	Mooring places	22

5.2 Verification and Validation

In this sub-chapter, it is tested if the model is fit for use in this research. This starts with the verification, where it is tested if the model is implemented correctly. Next, validation is performed, where it is tested if the model outputs are corresponding with real-world values.

5.2.1 Verification

Verification is the process of testing if the model is implemented correctly . With the test performed in the verification, it can be seen if the model performs as expected and intended. Two methods of model verification have been applied. First, a visual inspection is performed. With this visual inspection, the model behaviour of a single run is watched. Second, many runs were performed, looking at the model output behaviour.

Visual inspection of the model was performed with only a few vessels, and for some cases specific parameters have been changed to see if the model responds according to the expectation. Here, several different elements of the model were inspected. This will be elaborated upon next by looking at the cargo vessel generation, anchorage behaviour, pilot boarding behaviour, tug connect behaviour, terminal operations and setting output values.

Cargo vessel generation

For the cargo vessel generation, first the amount of vessels generated is checked. There should be 42 vessels generated each day, with some variation. In the inspection, exactly 42 vessels were generated each day. After the cargo vessel is generated, the vessel specific attributes have to be set. These include the vessel class, tugs needed, unload time and length. After vessel generation, these values have been set for each inspected vessel.

Anchorage behaviour

Vessels should only go to anchor when there is no room at the terminal. To inspect if the anchorage behaviour indeed sends vessels to anchor if there is no room at the terminal, all vessels have been given the same destination (Calland). Now, the amount of moorings for Calland have been set to 0. This should result in all vessels generated going to anchor. All vessels indeed went to the anchorage.

Another test was performed by giving all vessels the destination Calland, and putting the amount of moorings at the terminal at infinity. This should result in no vessels going to anchor. With this inspection, indeed no vessels went to anchor.

Pilot boarding behaviour

With the pilot boarding, it is important that every vessel has a pilot boarded. This is checked by looking into vessels leaving the pilot boarding station, where every vessel had a pilot boarded. It is also checked that every pilot is dropped off at the pilot boarding location with a pilot vessel, which has been confirmed to be the case.

Tug connect behaviour

For tug connection, the vessel primarily need to sail to the correct tug connection point, which corresponds with the destination terminal. Therefore, it has first been checked that vessels sail to the corresponding connection point by watching individual vessels based on their destination terminal. When the vessel arrives at the tug connection point, it is checked that the right amount of tugs are connected to the vessel, based on the tugs needed variable of that specific vessel, which was found to be implemented correctly.

Terminal operations

Upon arriving at the terminal, the vessel first has to disconnect the tugs. It is checked that all tugs are disconnected. Next the vessel has to disembark its pilot, which was successfully checked as well. Next, the vessel has to park at the terminal node for the duration of the vessel variable UnLoading time. One hour prior to departure the right amount of tugs and pilot are called, after which first the pilot will board the vessel. Next, the tugs will be connected in the right amount, and the vessel departs the terminal. All these steps were checked, and correctly executed by the model.

5.2.2 Calibration

The calibration of the model was performed as part of the verification. The calibration of the model was easy, with little deviation from the validation data on the initial model implementation. With small increases of the calibration value, a very small difference from the calibration data was found. The validation process of the average section speed is discussed below. Next, the calibration of the pilots and tugs was performed.

Section speed

The model is calibrated on the turnaround time of vessels. Here, the section speed variable is changed to calibrate the model according to the data on turnaround times retrieved from the thesis of Verduijn (2019). Different section speed factors have been used. Since in the base case the turnaround times were a little higher than in the base case, several 10% increases of the average section speed have been performed. The best result was achieved by a section speed of 1.1, while the outcomes on the other factors can be found in Appendix B. Since the section speed was assumed to be the average between the minimum and maximum values allowed at this section, this increase is still within the range of possible section speeds. The results for this calibration on each vessel class can be seen in table 5.2.

Table 5.2: Calibration outcome on section speed 1.1

Vessel Class	**1**	**2**	**31**	**32**	**4**	**5**	**6**	**Total**
Calibration value	1,22	1,38	1,48	1,40	1,47	1,65	1,60	1,46
Percentual deviation in model (1.1)	-3,98%	-5,88%	4,80%	2,75%	-22,00%	7,11%	19,28%	0,30%

Number of pilots and number of tugs

In the base-case, the number of pilots have to be determined. A system expert has been consulted on the values to calibrate for. This resulted in the following working method:

1. Make an experiment for 16 until 20 pilots
2. In every experiment, run with 7 till 15 tugs
3. Find the value where the average waiting time for pilots is stabilizing and the average time waiting for tugs is stabilizing
4. Consult the expert on which average waiting time for both pilots and tugs are plausible

This process resulted in 17 pilots and 10 tugs for the base case. The full methodology and outcomes of this calibration can be found in Appendix B.

5.2.3 Validation

In the validation of the model it is checked if the output values of the model correspond with real-world data. The validation is performed on the piloting time dataset, retrieved from the thesis of Verduijn (2019). This validation is performed for the piloting times to every terminal. The results of the validation can be seen in table 5.3. With this metric it can be tested if the model values are corresponding with the real-world values. The piloting time is a good representation of the main model output, average time in system of vessels.

Table 5.3: Validation outcomes per terminal

Terminal	Validation Value (Hours)	Difference (Hours)
Calland	2,31261	0,38539
MOT	2,24537	1,76963
Petroleum6	2,10977	0,26423
ECTAmazone	2,59839	-0,21039
EMOMissisippi	2,30424	-0,20824
ECTEurope	2,24064	-0,25964
APM	2,42266	-0,23266
Euromaxx	2,41489	-0,40789
MW	3,24095	0,15205
RWGAPMT	3,24066	-0,65866
Petroleum3_1	3,08552	-0,20152
Petroleum3_2	3,05545	-0,17145
TweedeWerkhaven	3,03102	-0,06002
Botlek	3,15283	-0,07483
	Total difference (hours)	0,086

The deviation from the validation values is 0.086 hours, which is an 3.22% deviation.

5.2.4 Fitness of the model

The verification showed that the model is implemented correctly with regard to the core functions of the model: Vessel generation, anchorage behaviour, pilot boarding behaviour, tug connect behaviour and terminal behaviour. The validation showed that the model produces values close to the observed real-world data. The model had a deviation of less than 4% on the validation data. Therefore, it is deemed that the model is fit for use in this research.

6. Experimentation

In this chapter, the results of the experiments will be elaborated upon. This will start with the base-case, followed by Pandemic, Accident, Suez-Canal blockage, Weather and Cyber Attack. For each disruption this chapter first discusses the disruption, then the resilience results, policy mitigation results and ends with the capacity mitigation results. Only the relevant outcomes will be discussed in this chapter, while the outcomes for all experiments on all mitigation strategies can be found in Appendix C, together with a table of all results on the resilience parameters.

6.1 Base case

With the values determined in the calibration section, the base case was run. This resulted in the graph shown in figure 6.1.

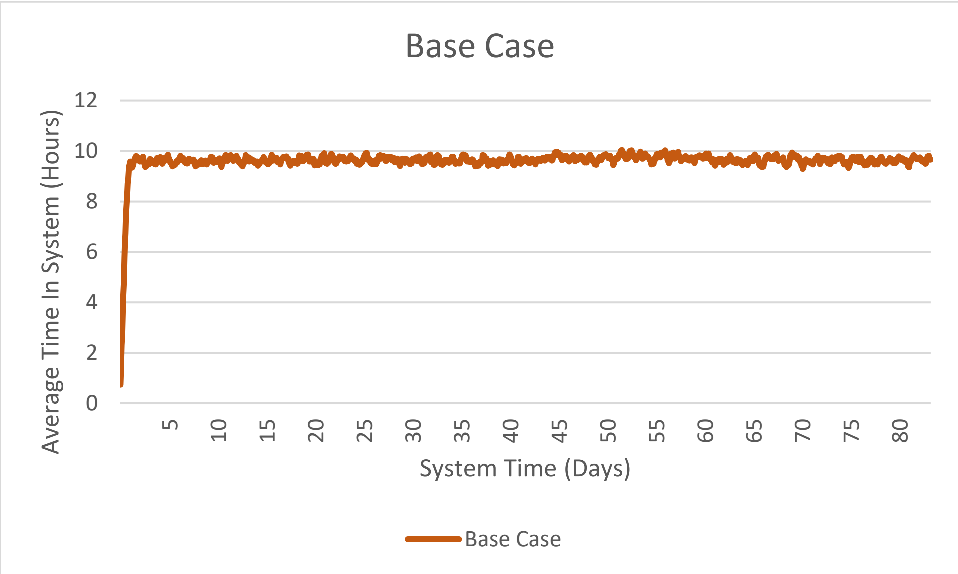


Figure 6.1: Base Case run

This graph shows that after the model has warmed up, the average time in system of all vessels in the harbour stabilizes around 10 hours. At this value, the harbour system is stable, with minor deviations from this average time in system. These deviations can be expected, due to stochasticity in the model, like vessel arrivals, vessel classes, vessel destinations and their corresponding unloading times.

This 10 hours is thus the business-as-usual value of the port. Now that is clear how the average time in system in the port behaves under normal circumstances, disruptions will take place in the port. This starts from the pandemic disruption and ends with the Cyber Attack disruption. This order of disruptions is based on the severity of the impact on the system.

6.2 Pandemic

With a pandemic, the impact is on the ports' labour force. Therefore, in this pandemic scenario the number of pilots is nearly halved from 17 to 9, the number of tugs is halved from 10 to 5 and the unloading times of vessels is increased with 50%. The decrease of pilots and tugs are deemed due to half the working force being affected by the pandemic, and the increase in unloading time is due to terminal employees being sick, leading to less unloading capacity and longer unloading times. Since there are also many terminals with less labour needed for unloading, like oil and chemical terminals, the effect on the unloading time is deemed smaller.

6.2.1 Result Pandemic

The pandemic starts in the 8th day of the model run and has a duration of three weeks. In figure 6.2 the effect of the pandemic on the average time in system is given. It can be seen that immediately after the pandemic starts, the average time in system starts to increase. At the end of the pandemic, the average time in system increased from 10 hours to over 70 hours. After the end of the pandemic, the average time in system increases for nearly 4 days up until an average time in system of 78 hours before starting to drop to the business-as-usual value, which can be explained by the backlog of vessels and lack of pilot and tug resources. The business-as-usual value is achieved around day 47, 18 days after the end of the pandemic. In this scenario the duration to go back to the business-as-usual value is less than the duration of the disruption and the slope of the recovery phase towards the business-as-usual value is steep. Next, the results of the mitigation strategies will be discussed.

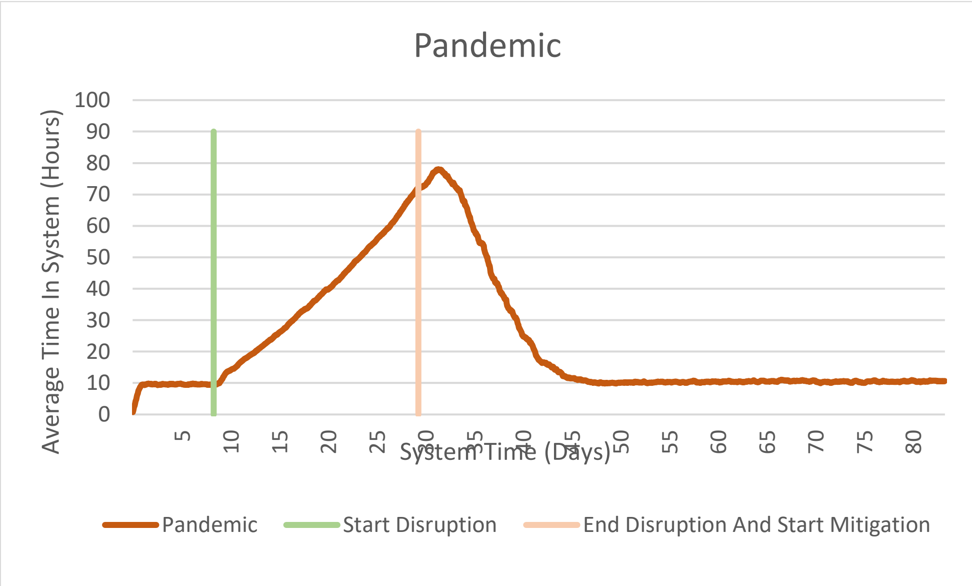


Figure 6.2: Results of a pandemic on the base case

6.2.2 Policy mitigation results

In figure 6.3 the results of the three vessel priority policy strategies are shown. Since the effects are very small, a more detailed figure from the end of pandemic to business-as-usual values is given in figure 6.4. It can be seen that all strategies slightly reduce the maximum average time in system. With all strategies, the time it takes to get back to the business-as-usual value is very similar to the base case scenario. In total, the largest vessel first strategy decreases the resilience with 5% while for less tugs first and smallest vessel first the effects improve the resilience by 5% and 8% respectively.

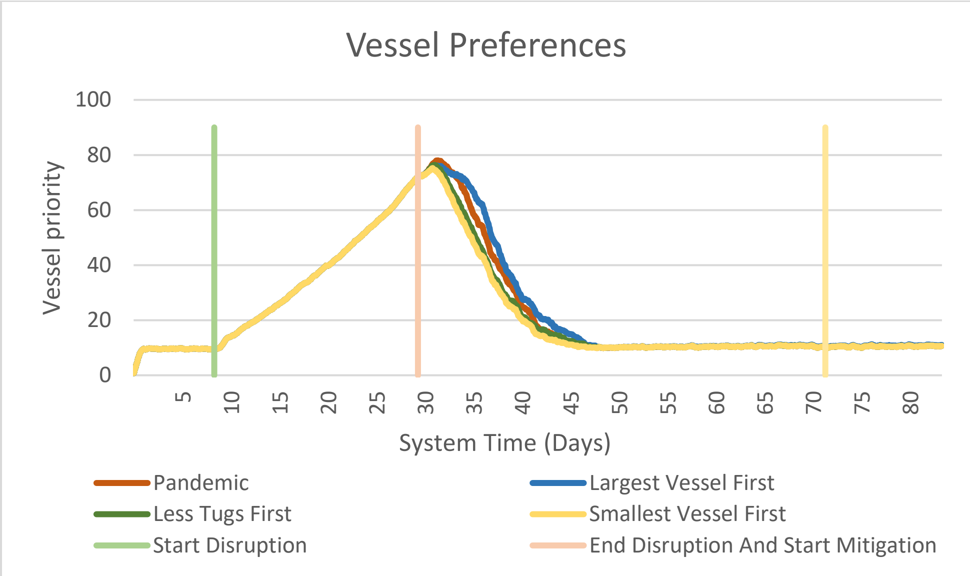


Figure 6.3: Results of vessel priority strategies on a pandemic

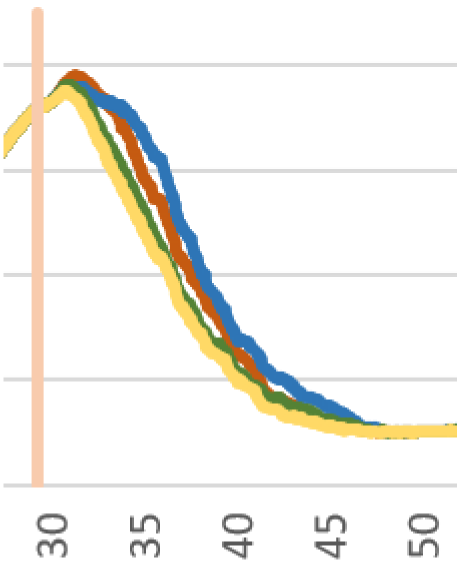


Figure 6.4: Close look at the vessel priority results

The results for increasing the average speed can be seen in figure 6.5. The effect of this mitigation strategy improves the time to go back to the business-as-usual value. The time to go back to business-as-usual values is decreased with around 40 hours, increasing the resilience with around 4%.

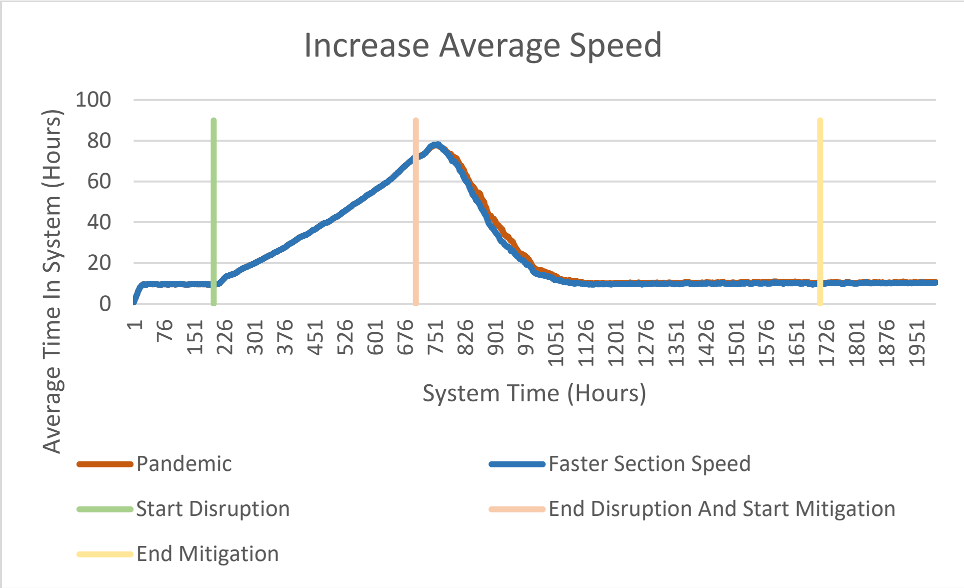


Figure 6.5: Results of increasing the average speed with a Pandemic

6.2.3 Capacity mitigation results

The capacity mitigation showed less than 1% improvement when increasing pilots, and up to 8% improvement when increasing tugs. Figure 6.6 shows the results of increasing tugs and a simultaneous increase of pilots and tugs, and figure 6.7 shows a closeup on the part from the end of the pandemic until the business-as-usual value. The simultaneous increase in pilots and tugs improves the resilience with 11%, which is more than the sum of the individual contributions of pilots and tugs with an extra improvement of 2.3%, and is therefore the best strategy of this disruption.

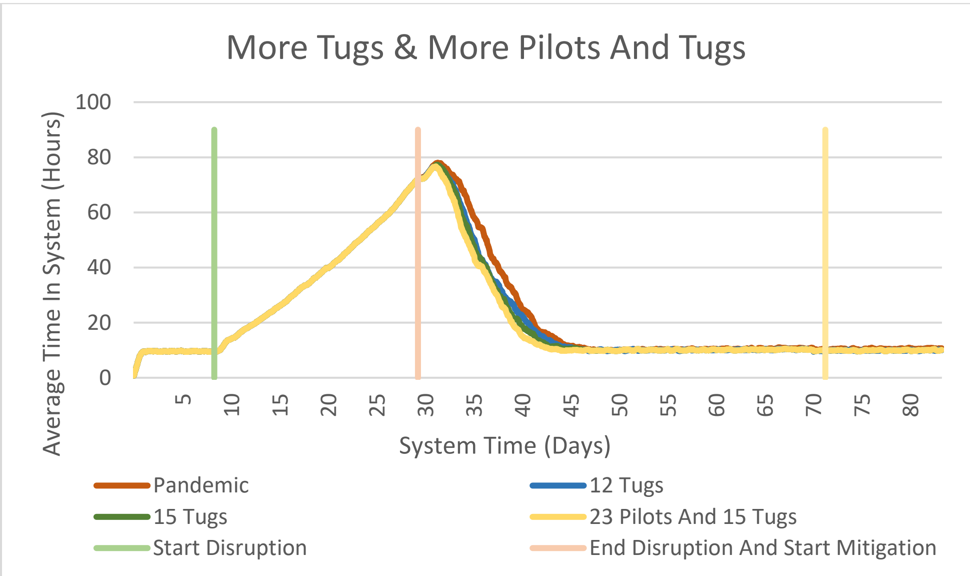


Figure 6.6: Result of increasing tugs, and pilots and tugs after a Pandemic

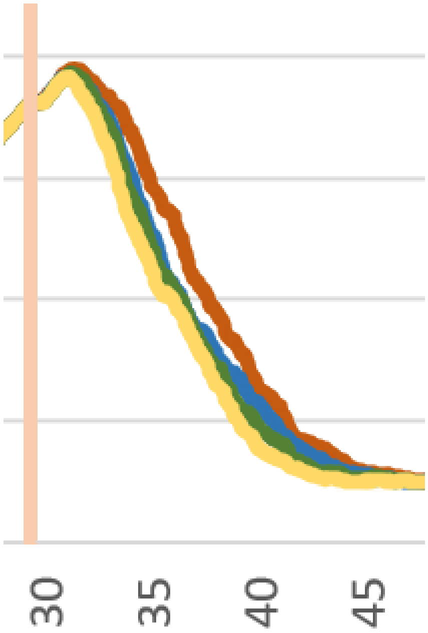


Figure 6.7: Close up on tugs and pilots result with a Pandemic

6.3 Accident

In the accident scenario, an accident at the entrance of the Maasvlakte is simulated. This could be due to a sunken vessel, leading to a complete blockage of this route. The location of the simulated accident can be seen in Figure 6.8. All terminals at the Maasvlakte are affected, and cannot receive new vessels until the disruption has been lifted. It has been chosen to take 5 days for this disruption, and the accident happens in the 8th day of system time. The accident is therefore dealt with at day 13.

Figure 6.8: Location of simulated accident

6.3.1 Result Accident

The response of the average time in system with this disruption can be seen in Figure 6.9. This figure shows that shortly after the accident happens, the average time in system increases. When at day 13 the disruption is over, the average time in system keeps increasing for a short amount of time before starting to decrease. The maximum average time in system with this disruption is around 55 hours, which means that vessels spend over 2 days on average in port. Around 21 days, the average time in system is back to the normal value of 10 hours. Next, mitigation strategies to improve the resilience of the port will be discussed.

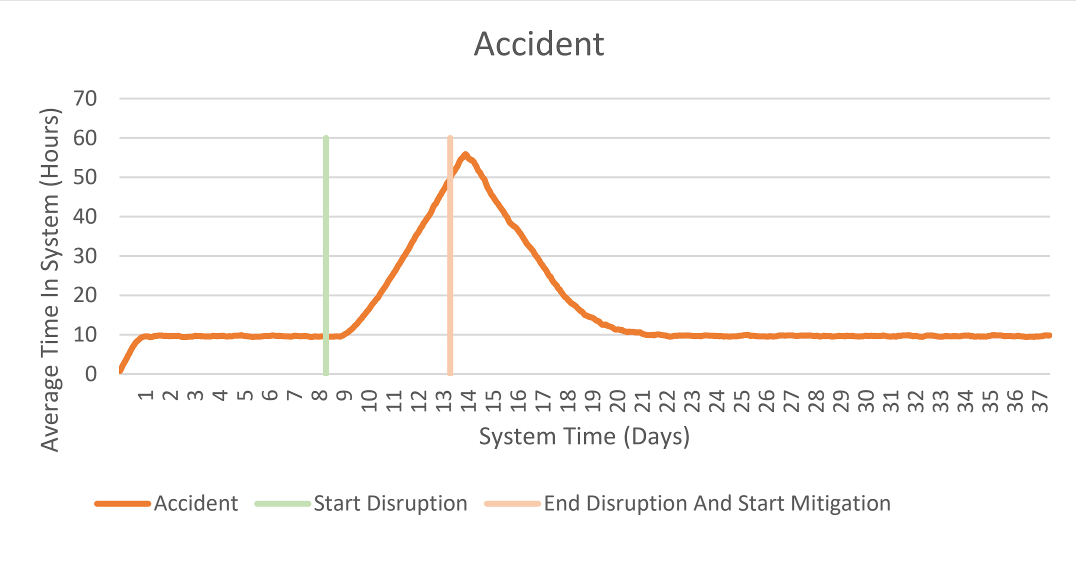


Figure 6.9: Result of accident disruption

6.3.2 Policy mitigation results

From the policy mitigation options, the first interesting result to discuss is the largest vessel first priority strategy. The result of this strategy can be seen in figure 6.10, where it can clearly be seen that the strategy worsens the resilience of the port. After the disruption has been lifted, the average time in system stays at a higher value for a longer time. Also, the time it takes to get back to the business-as-usual value is longer then with the base-case scenario. This effect results in a decrease of the resilience of close to 19%. First, this can be explained by the large amount of terminals on the Maasvlakte which are container terminals, and therefore have a quay length. When letting the largest vessels in first, the quay length is occupied by lesser vessels then in the base-case. Since every vessel has the same contribution to the average time in system, this leads to an overall higher average time in system. Second, larger vessels often require more tugs. This means that especially the bump, which is circled in figure 6.11, can be accredited to delays due to a shortage on tugs. The decrease of the resilience can therefore be accredited to both the vessel length, leading to less vessels at the terminals, and the amount of tugs larger vessels need which lead to increased waiting times for tugs.

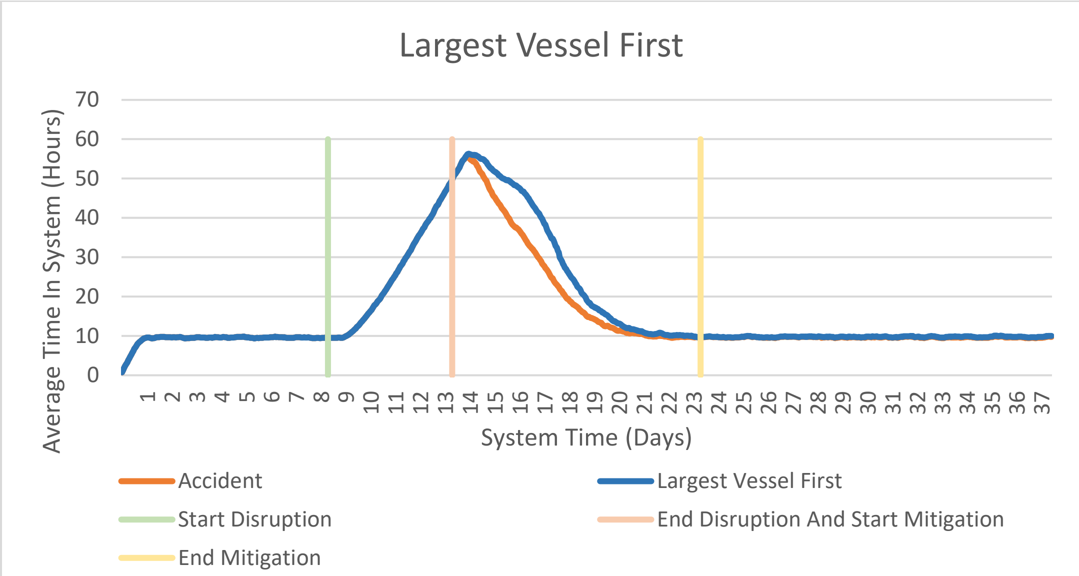


Figure 6.10: Largest Vessel First strategy with an Accident

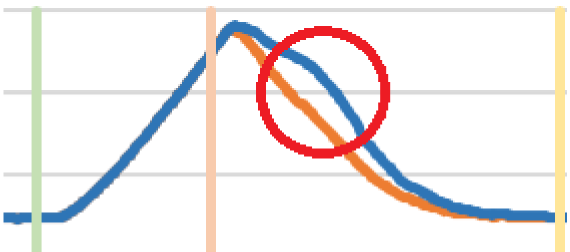


Figure 6.11: Delay created by tugs

Increasing the average speed in the harbour improves the resilience, which can be seen in figure 6.12. Shortly after the disruption has been lifted the average time in system starts to decrease faster than the base-case scenario. This result can easily be understood by the increased speed in the harbour. First, when the speed is increased, vessels have a shorter time to sail, leading to less time in system. Second, by sailing faster the piloting times for pilots and towing times for tugs decrease, which leads to pilots and tugs being able to handle more vessels in the same time period. This leads to an improvement of 19% on the resilience.

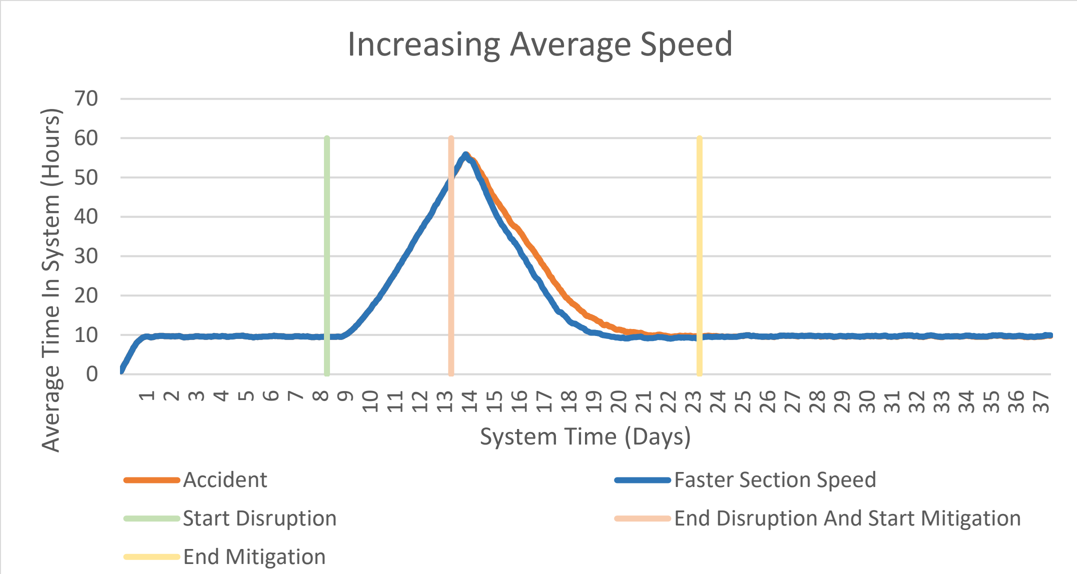


Figure 6.12: Faster Section Speed strategy with an Accident

The less tugs first and smallest vessel first decreased the resilience between the 1% and 2%, which are minor effects thus these strategies will not be discussed.

6.3.3 Capacity mitigation results

With the capacity mitigation results, first it was found that increasing the amount of tugs improved the resilience only up to 5%. Second, increasing the amount of pilots increased the resilience, which can be seen in Figure 6.13. Here, it can be seen that the average time in system decreases faster than with the base-case. Also, the business-as-usual value is achieved around 30 hours earlier then in the base case. Therefore, increasing the amount of pilots increases the resilience with around 13% with 20 pilots, and 18% with 23 pilots.

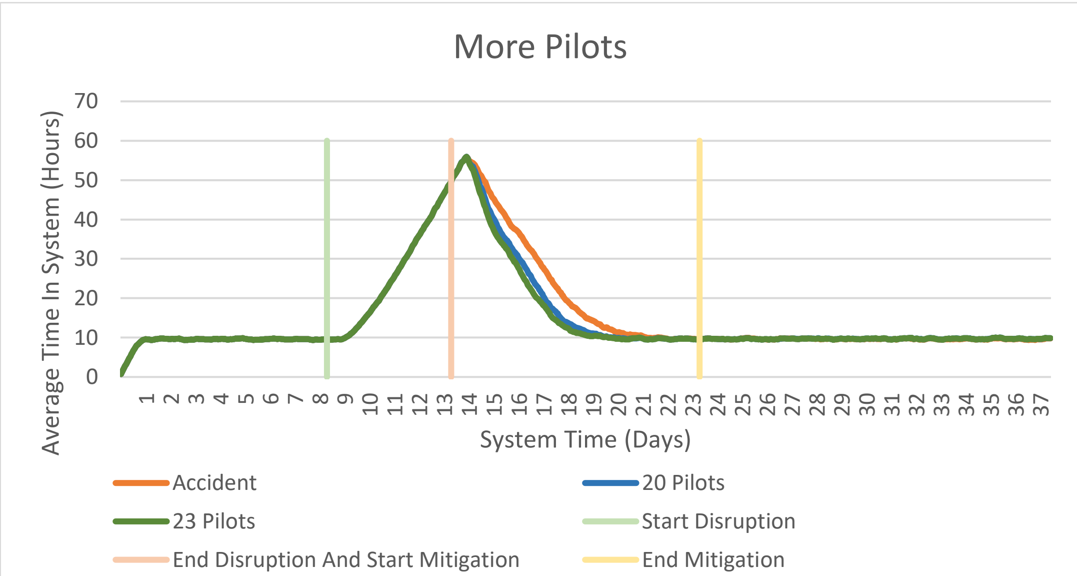


Figure 6.13: Increasing the amount of pilots after an accident

Last, a simultaneous increase in the amount of pilots and tugs increases the resilience of the ports with nearly 24%, which can be seen in figure 6.14. This result shows that for this scenario, the simultaneous increase in pilots and tugs yield larger benefits then only increasing with 6 pilots and 5 tugs, resulting in an extra improvement in the resilience of 1.25% compared to the individual contributions.

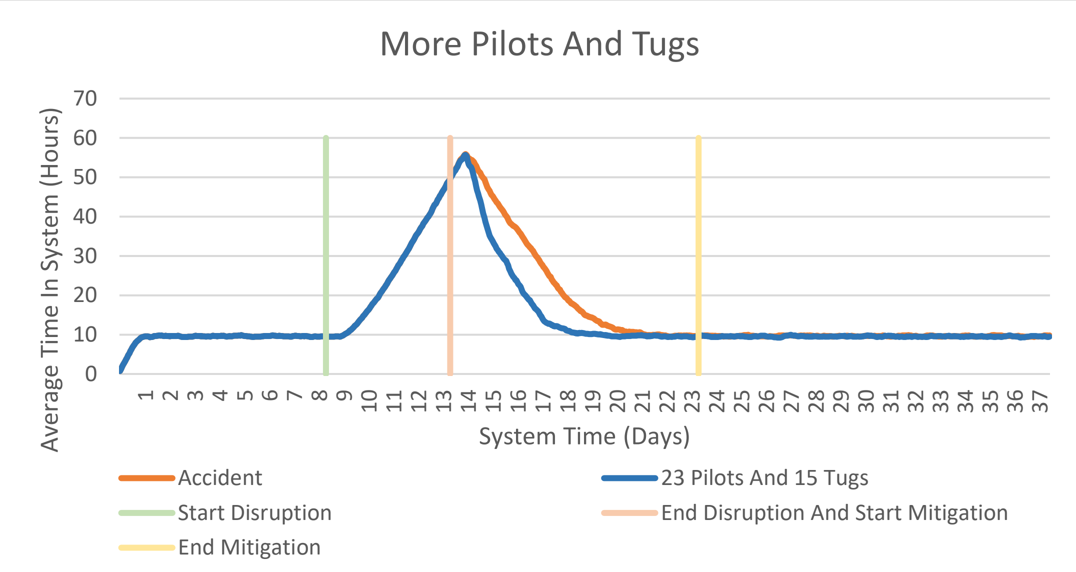


Figure 6.14: Increasing both pilots and tugs after an accident

6.4 Suez Canal Blockage

The Suez Canal blockage scenario simulates disruptions at other locations then the port, which result in vessel fluctuations. The result of this blockage for the Port of Rotterdam was a variation in vessel arrivals, which can be seen in figure 6.15. According to Pals (2016), during one week a total of 67 vessels less came in to port. This results in a reduction of the vessel arrival factor from 42 to 32 vessels a day for the duration of this week. After this week, the blockage was lifted. There were 3 cancellations, and the backlog from the Suez Canal comes to the port in 3 days. This resulted in 64 extra vessels in 3 days, thus a vessel arrival factor of 64 vessels.

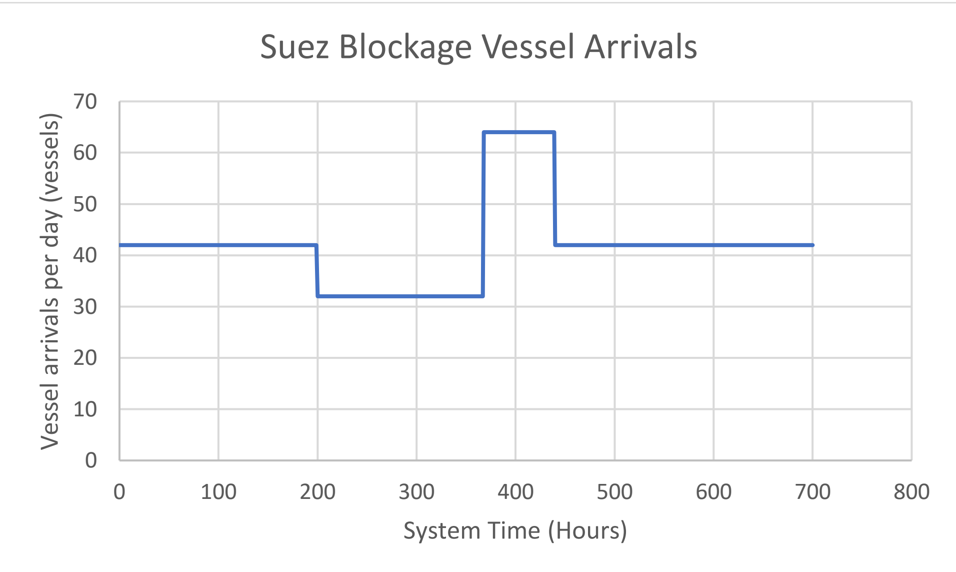


Figure 6.15: Vessel fluctuations during the Suez Canal Blockage

6.4.1 Result Suez Canal Blockage

Figure 6.16 show the results of the Suez Canal blockage on the base case. When the daily vessel arrivals are reduced, the average time in system reduces slightly over time. This slight reduction is due to the unloading and sailing times of vessels, which make the average time in system not decrease immediately. In the business-as-usual value, there are limited waiting times, and thus less vessels do not reduce the average time in system much when less vessels arrive. However, when the backlog of vessels comes in, it can be seen that first the average time in system starts to decrease a bit. This can be explained by small vessels, with destinations close to the port entry being handled rapidly. When the amount of vessels is low, there is a surplus of tugs and pilots, which are immediately available to serve vessels. Next, the average time in system starts to increase until around 14 hours at the end of the higher vessel arrivals. Now, a backlog of vessels causes the average time in system to still increase, up until a value of around 15 hours. Shortly after, the average system time starts to drop to the business as usual value, which is achieved around day 21, which is only 60 hours after the higher vessel arrival has stopped. Next, the effect of different mitigation strategies will be discussed.

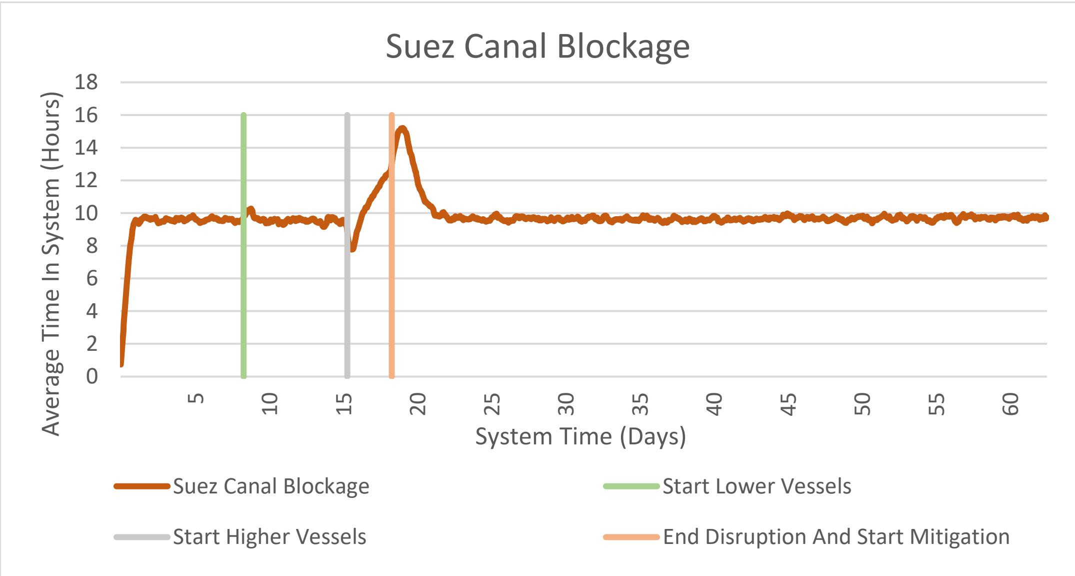


Figure 6.16 : Results of the Suez Canal blockage on the base case

6.4.2 Policy mitigation results

With regard to the vessel priority mitigation strategies, no improvement or decrease in the resilience was found, with deviations close to 0%. The effect of increasing the average speed is shown in figure 6.17, where the maximum average time in system is decreased 1 hour compared to the base case and the business-as-usual value is achieved 20 hours earlier. The faster sailing time in port reduces the sailing time of vessels, piloting time and towing time. Therefore, resources are used for shorter, making waiting times on pilots and tugs smaller. This resulted in an improvement of the resilience of 21% with the average speed increase.

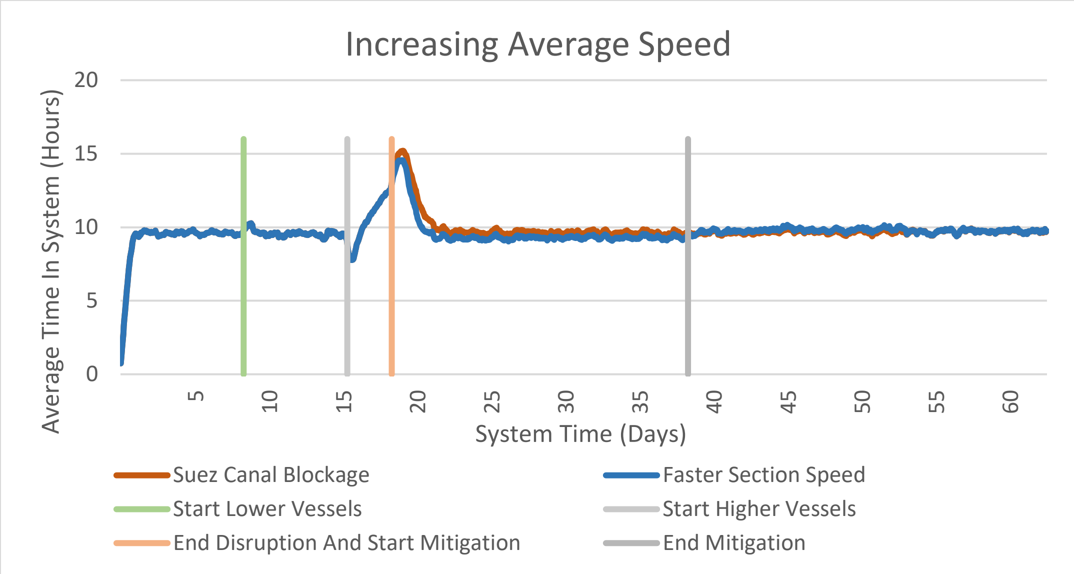


Figure 6.17: Increasing average speed with the Suez Canal Blockage

6.4.3 Capacity mitigation results

The capacity mitigation strategies proved to improve the resilience, with the smallest improvement of 4% found when increasing the amount of tugs. Figure 6.18 shows the results of increasing the amount of pilots, which reduced the maximum average time in system with 1 hour and got back to the business-as-usual value 20 hours earlier then the base-case. Together, this improved the resilience with 22% for 20 pilots and 28% for 23 pilots. This improvement in the resilience shows that most of the increase in the maximum average speed and duration of the recovery can be accredited to waiting times for pilots. Increasing the amount of pilots limit the waiting times, thus improving the resilience.

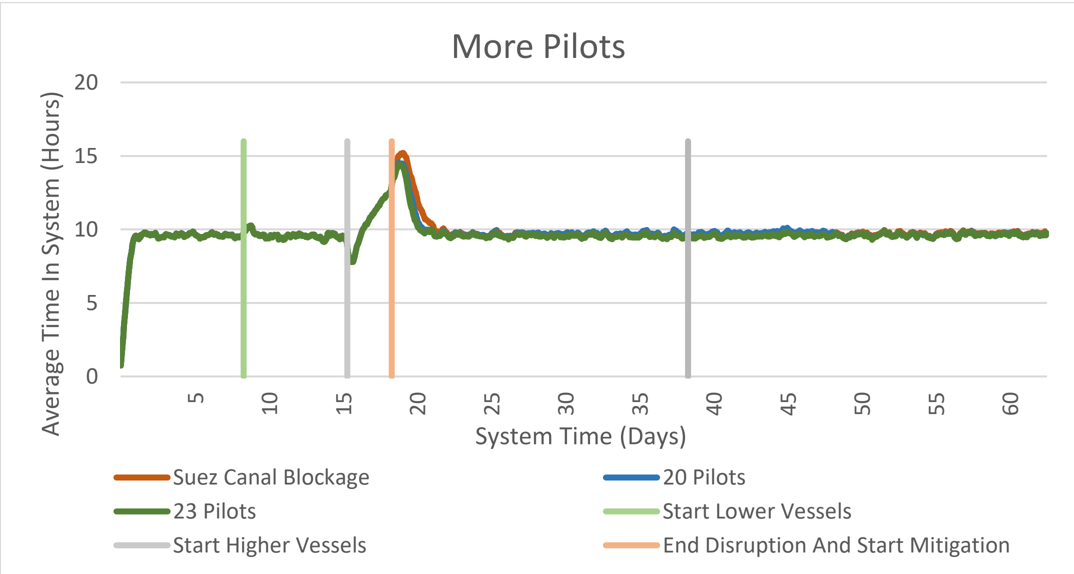


Figure 6.18: Result of increasing pilots with Suez Canal Blockage

Simultaneously increasing the amount of pilots and tugs resulted in the graph of figure 6.19. This graph shows a reduction of the maximum average time in system of around 1 hours, and a decrease in the duration to get back to the business as usual value of nearly 30 hours. These effects improved the resilience with 30%, which is similar to the individual contributions of tugs and pilots. This mitigation strategy improved the resilience most in this scenario.

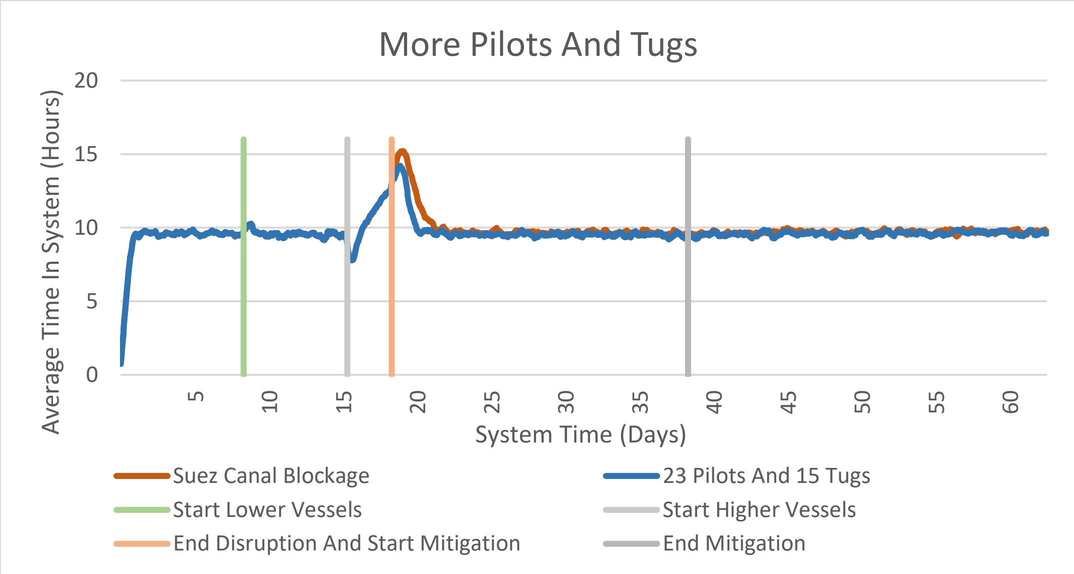


Figure 6.19: Increasing both pilots and tugs with the Suez Canal Blockage

6.5 Weather

The weather scenario simulates an extreme weather event, like high wind speeds, ice in port or high waves, leading to a complete port closure for the duration of two days.

6.5.1 Result Weather

The results of this scenario on the base-case are shown in figure 6.20. This figure shows that once the port closes in the 8th day, the average time in system of vessels start to increase rapidly. After the 2 days of port closure, the average time in system increased from 10 hours to 33 hours. When the port opens after the disruption, the first bulk of vessels goes in, leading to a slide decrease in the average time in system. Shortly after, the average time in system starts to increase again, which is caused by a backlog of vessel and shortage on resources. This peaks at a maximum average time in system of 36 hours, after which it starts to decrease to the business-as-usual value which is achieved in the 20th day of system time, which is 10 days after the disruption has ended. Therefore, the effect on the average time in system of this disruption is severe, thus the effect of the mitigation strategies will be elaborated next.

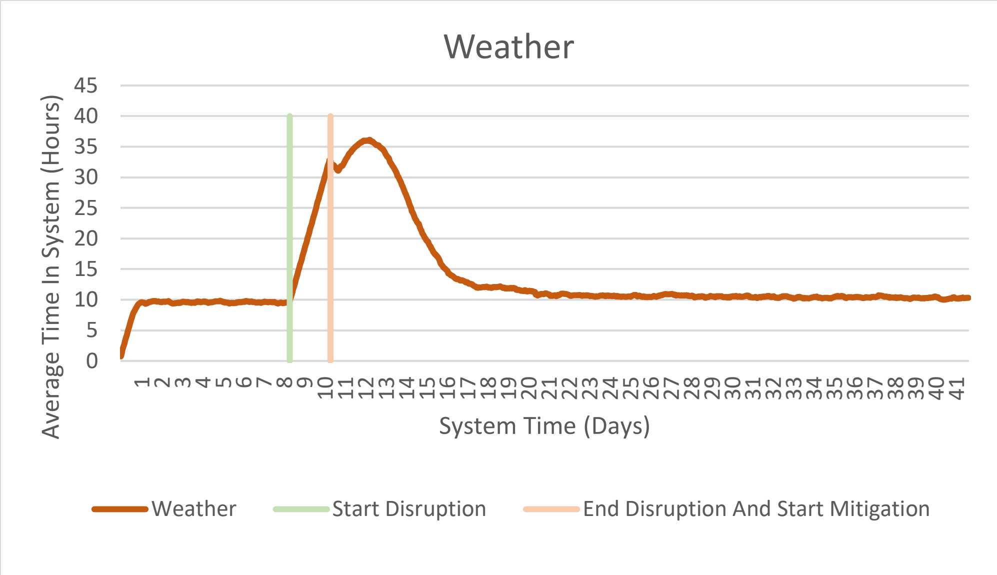


Figure 6.20: Results of Extreme Weather on the base case

6.5.2 Policy mitigation results

The smallest vessel first vessel priority strategy performed equal to the base case, while the less tugs first and largest vessel first decreased the resilience up to 2%. However, increasing the average speed improved the resilience, which can be seen in the graph in figure 6.21. The maximum average time in system decreased over 1 hours, and the business-as-usual value is achieved over 2 days earlier then the base case. Together, this improved the resilience over 18%.

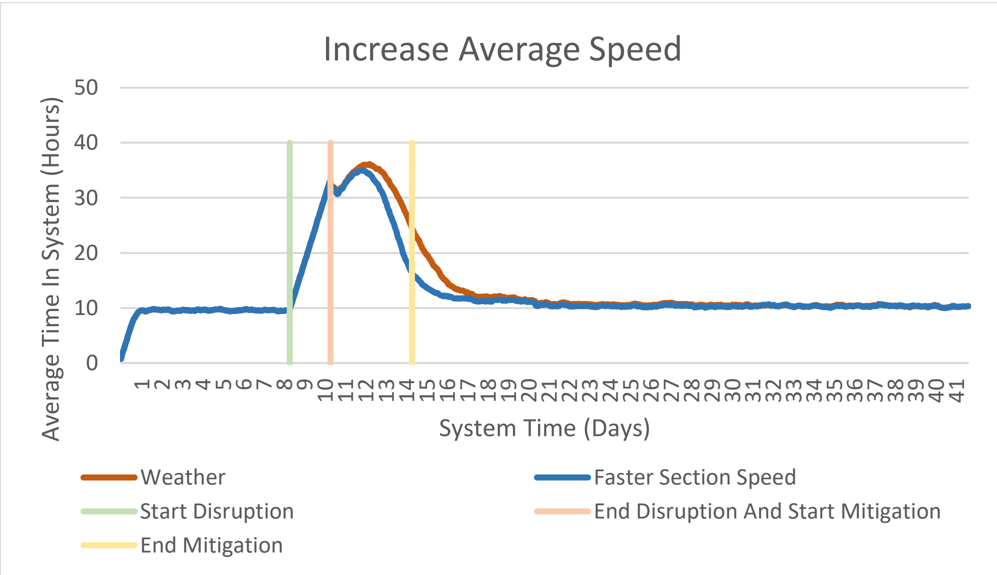


Figure 6.21: Result of increasing the average speed on Extreme Weather

6.5.3 Capacity mitigation results

Increasing the amount of tugs in port showed little improvement in the resilience of up to 6%. Increasing the amount of pilots yielded better results, which can be seen in figure 6.22. The maximum average time in system is decreased by approximately 3 hours, and the business-as-usual value is achieved over 4 days sooner. This resulted in an improvement of the resilience of 31% with 20 pilots and 42% with 23 pilots, showing that pilot waiting times are severely influencing the resilience.

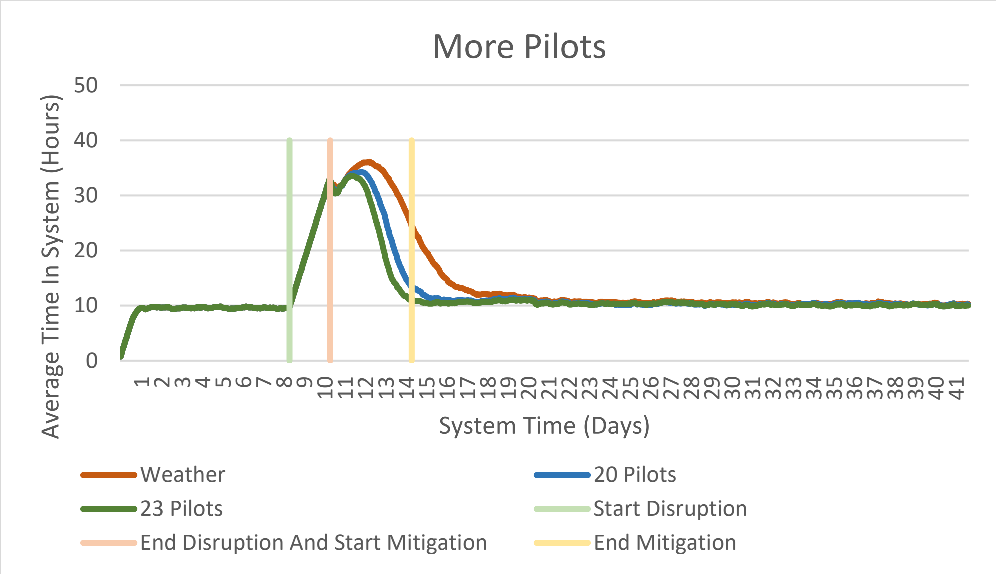


Figure 6.22: Results on increasing the amount of pilots on Extreme Weather

The effect of increasing the amount of pilots and tugs simultaneously are shown in figure 6.23. This graph shows that the maximum average time in system is reduced, so that this maximum is close to the value at the end of the disruption. Thereby, the recovery to the business-as-usual value is achieved 5 days earlier than in the base-case. This improved the resilience with 46%, resulting in the best improvement of the resilience of all mitigation strategies in this scenario.

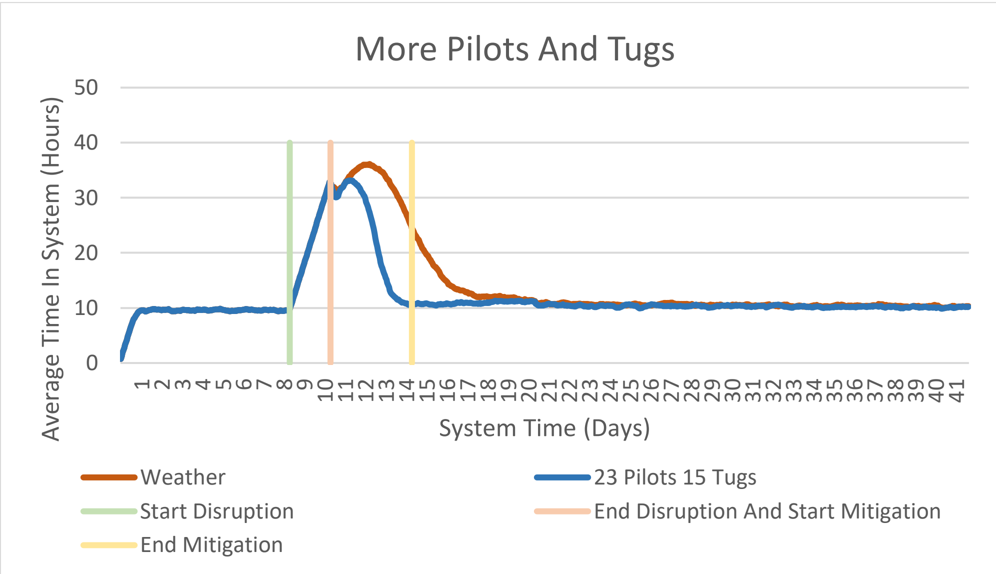


Figure 6.23: Results on increasing pilots and tugs on weather

6.6 Cyber Attack

The cyber-attack scenario simulates an cyber-attack on the Calland terminal in the Port of Rotterdam, which represent multiple terminals in the real-world. The affected terminals can be seen in figure 6.24. According to a report of Statista (2022) the average duration of disruption with an cyber-attack is 20 days. In this scenario, the Calland terminal will thus be unable to handle incoming vessels for a duration of 20 days.

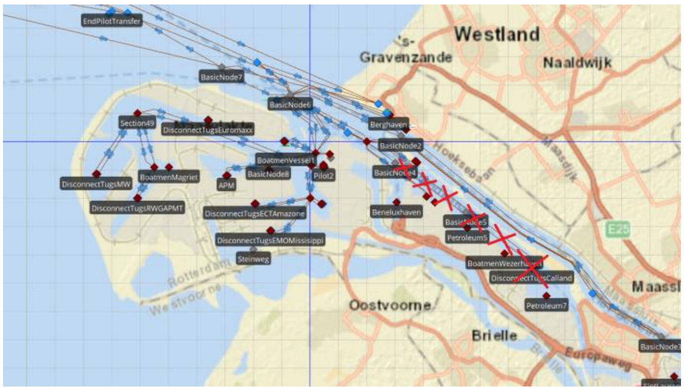


Figure 6.24: Location of Calland terminal and unavailable section

6.6.1 Result Cyber Attack

In the 8th day of system time the cyber-attack starts, and stops in the 28th day. The results on the average time in system of this disruption are shown in figure 6.25. In this figure it can be seen that directly after the cyber-attack happens, the average time in system starts increasing. This is caused by the vessels designated for the Calland terminal being at anchor due to the closure of this terminal, leading to an average time in system of 220 hours at the end of the disruption. When the disruption has ended the average time in system decreases a bit due to idle pilots and tugs immediately responding, after which it increases again up to a maximum time in system of 340 hours. This second increase is due to a lack of resources in the Nautical Chain to handle the backlog of vessels. Due to this lack of resources, vessels for other destinations start to be delayed too, adding to the increase of the average time in system. After this peak, the business-as-usual value is reached at day 52, which is nearly 24 days after the end of the disruption. The effects of this disruption on the average time in system of vessels is large, which can be partly explained by the large amount of vessels designated for the Calland terminal, which is over 40% of all arriving vessels.

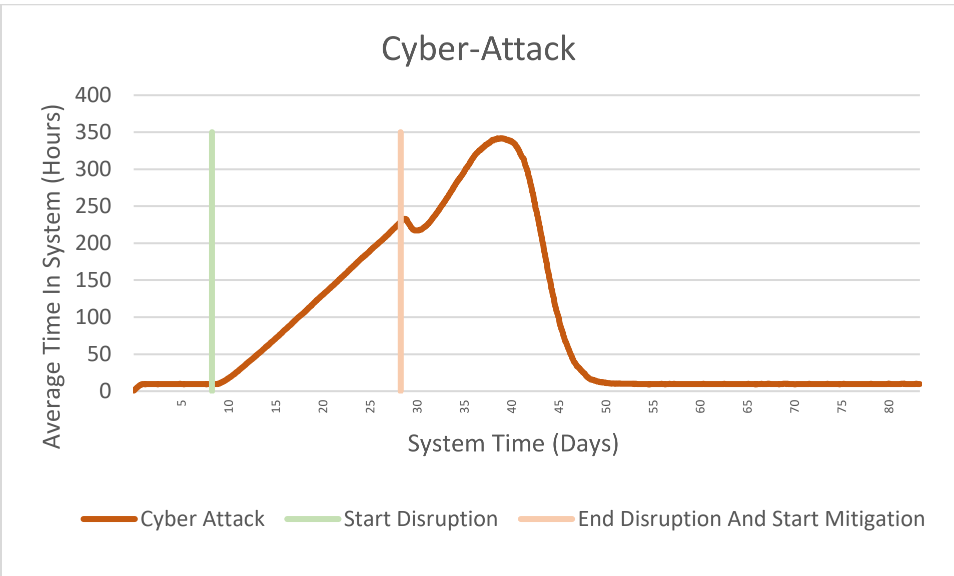


Figure 6.25: Result of a Cyber Attack on the average time in system

6.6.2 Policy mitigation results

Increasing the average speed in port increased the resilience, which can be seen in figure 6.26. This figure shows that the maximum average time in system is decreased with this mitigation strategy with 10 hours, and the time to get back to the business-as-usual value is improved with over 6 days. This lead to a total improvement of the resilience of 15% by increasing the average speed.

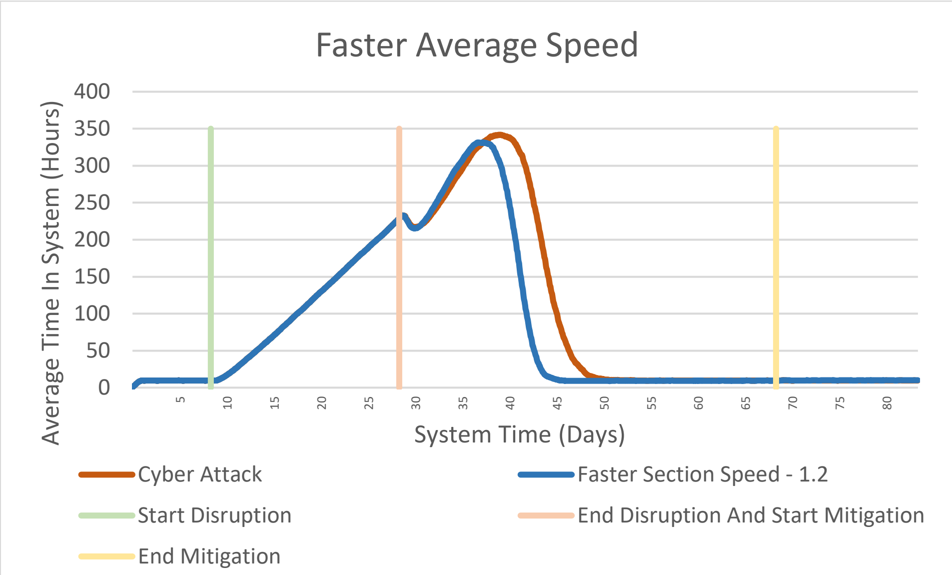


Figure 6.26: Increasing average speed with a Cyber Attack

Figure 6.27 show the results of the three vessel priority strategies where it can be seen that all three strategies reduce the maximum average time in system with this disruption. This improvement is the least with the largest vessel first strategy, and with this strategy the time to get back to the business-as-usual value is increased with nearly 3 days compared to the base-case. Larger vessels require more tugs, and therefore tug waiting times can explain the increase in reaching the business-as-usual value. Still, this mitigation strategy results in an improvement of the resilience of 5%. Next, the least tugs first priority strategy also reaches the business-as-usual value 3 days later compared to the base-case which can be accredited to a lot of tug demand at a later stage in the model, since the lowest tug demanding vessels got into port first. This strategy mitigates more on the maximum average time in system compared to the largest vessel first strategy, which is due to low tug waiting times. Together, this results in an increase of the resilience of 9%. Last, the smallest vessel first priority strategy reaches the business-as-usual value around the same time as the base case, and has the same improvement on decreasing the maximum average time in system as the less tugs first strategy. Therefore, this strategy performs best of the vessel priority strategies with an improvement of the resilience of 14%.

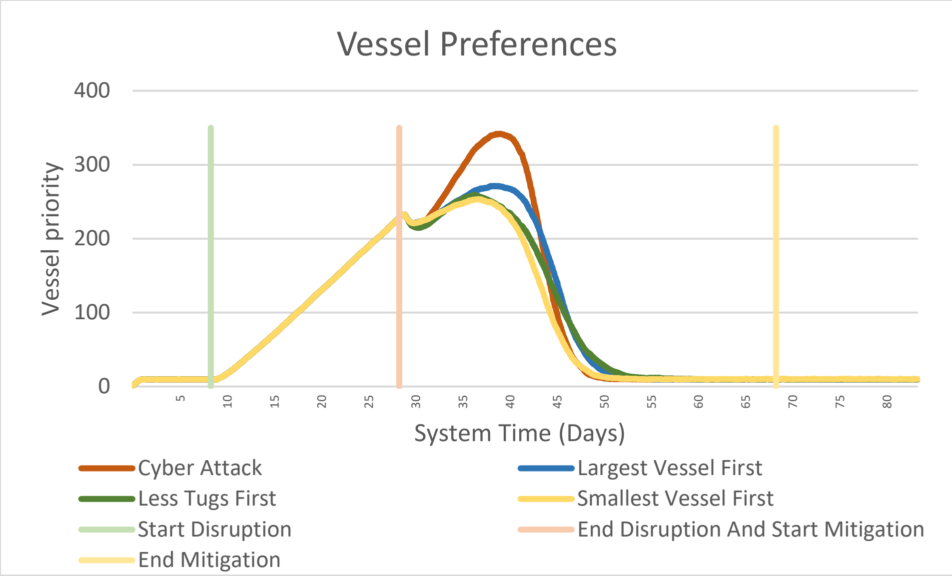


Figure 6.27: Different vessel priority's with a Cyber Attack

6.6.3 Capacity mitigation results

Increasing the amount of pilots increased the resilience, which can be seen in figure 6.28. When increasing with 3 pilots, the maximum average time in system is decreased with 16 hours, while the recovery to the business-as-usual value is achieved over 8 days sooner. This results in an improvement of the resilience of 21% for the increase to 20 pilots. Next, increasing the amount of pilots to 23 reduced the maximum average time in system with 28 hours, and the recovery to the business-as-usual value is improved with 10 days which resulted in an improvement of 29% to the resilience. These results can be accredited to the improved pilot resource, leading to lower waiting times for pilotage.

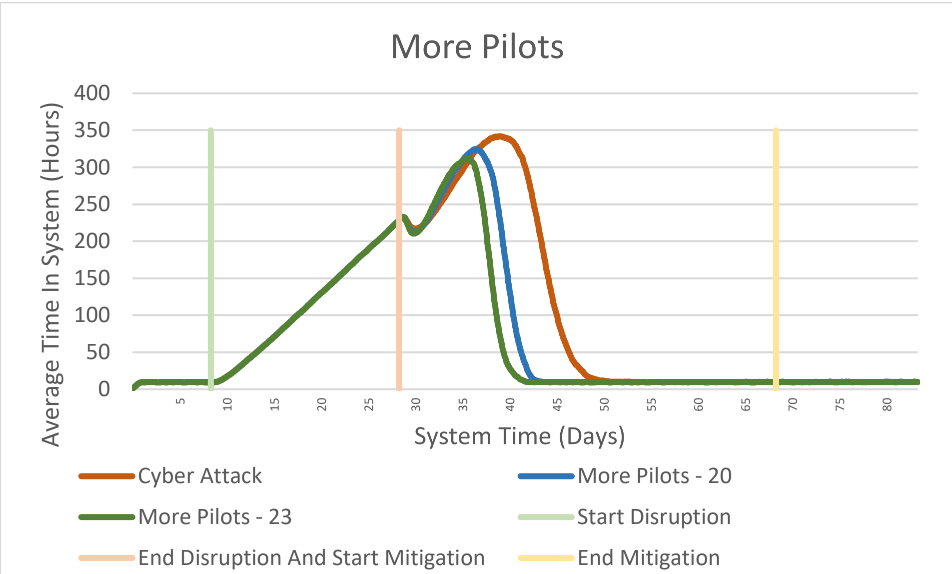


Figure 6.28: Increasing pilots after a Cyber Attack

Figure 6.29 shows both the results on increasing the amount of tugs, and a simultaneous increase of pilots and tugs. Starting with the tug increase, the results show little improvement compared to the base case resulting in improvements to the resilience of 4%. Simultaneously increasing the amount of pilots and tugs improve the resilience. The maximum average time in system is reduced by 35 hours and the recovery to the business-as-usual value is achieved nearly 13 days earlier. This results in an improvement of 36% of the resilience, which is nearly 3% more than the individual contributions of 23 pilots and 15 tugs. In this scenario, the simultaneous increase of pilots and tugs improves the resilience most of all mitigation strategies.

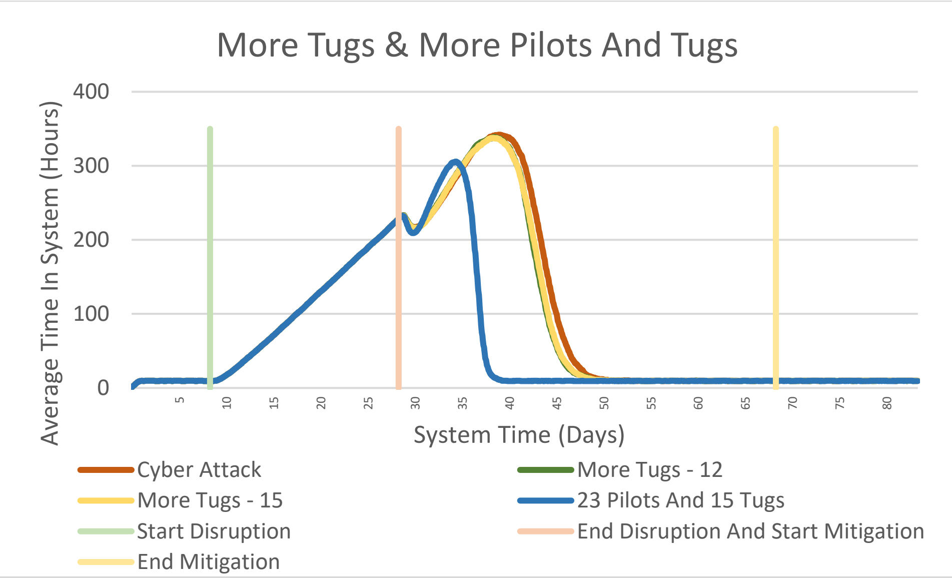


Figure 6.29: Increasing pilots and tugs after a Cyber Attack

6.7 Summary of the results on the disruptions

Pandemic

In the pandemic scenario, the largest improvement of the resilience was found with the simultaneous increase of pilots and tugs improving the resilience with 11%. The largest vessel first vessel priority strategy performed the worst, decreasing the resilience with 5%. The smallest vessel first priority strategy performed second best however, improving the resilience with over 8%. Increasing tugs improved the resilience up to 8%, while increasing pilots did not result in an improvement. The less tugs first priority strategy also improved the resilience with 5%, and increasing the average speed improved the resilience with close to 4%. The results show that except for the largest vessel first strategy and increasing pilots, all strategies improved the resilience. Most improvement for this scenario was found with a simultaneous increase in pilots and tugs.

Accident

The largest improvement to the resilience in the accident scenario was found with the simultaneous increase of pilots and tugs, improving the resilience with 24%. The largest vessel first performed worst, with a decrease of 18% on the resilience. The other vessel priority strategies also decrease the resilience with up to 2%. Increasing the amount of tugs improved the resilience 4% to 5%, while increasing the amount of pilots improved the resilience up to 18%. The vessel priority strategies all decreased the resilience, while all other strategies improved the resilience. Simultaneously increasing pilots and tugs improved the resilience in this scenario the most.

Suez Canal Blockage

The vessel fluctuations resulting from the Suez Canal blockage scenario showed that simultaneously increasing pilots and tugs provide the largest improvement on the resilience of 30%. The vessel priority strategies did not improve the resilience. Increasing tugs improved the resilience up to 5%, while increasing pilots improved the resilience up to 28%. Also, increasing the average speed improves the resilience with 21%. Besides the vessel priority strategies, all strategies improved the resilience. For this scenario, the simultaneous increase of pilots and tugs performed best.

Weather

In the weather scenario, simultaneously increasing the amount of pilots and tugs improved the resilience the most with an improvement of 46%, which is the highest improvement of the resilience found in this research. The vessel priority strategies did not improve the resilience. Increasing the amount of tugs improved the resilience up to nearly 6%, while increasing pilots showed large improvements to the resilience of up to nearly 42%. Increasing the section speeds improved the resilience with over 18%. In this scenario, all strategies except the vessel priority strategies improved the resilience. The largest improvement was found in the simultaneous increase of pilots and tugs, which is also the largest improvement found in this research.

Cyber Attack

The cyber-attack scenario showed large effects on the average time in system of vessels, where the largest improvement of the resilience was found in the simultaneous increase of pilots and tugs improving the resilience with 36%. All vessel priority strategies improved the resilience, with the lowest improvement being 5% for the largest vessel first strategy and the largest improvement of 14% for the smallest vessel first scenario. Increasing the amount of tugs performed worst improving the resilience, only improving around 4%, while increasing pilots improved the resilience up to 29%. Increasing the average speed improved the resilience with 15%, showing that all strategies improve the resilience in this scenario. The best improvement to the resilience was achieved with a simultaneous increase in pilots and tugs.

7. Discussion

This chapter discusses the main findings of the research.

The results found in this research contribute to the current knowledge in the literature. Nikghadam et al. (2021) found that pilots and tugs have a critical position in ports, and terminals have less of a critical role. The results of our research showed that pilots and tugs also have a critical position in improving the resilience of the Nautical Chain. However, when disruptions happen the results show that terminal capacity can become a limiting factor with the implementation of mitigation strategies. Therefore, the results show that the role of the terminals might be more influential then found by Nikghadam et al. (2021) when disruptions happen in ports. Second, Vanlaer et al. (2021) found that port authorities are well positioned to increase resilience in ports. This research found that the vessel priority mitigation strategies, one of the tools of the port authority, are not stable effective in improving the resilience of the Nautical Chain. Increasing the average speed in the harbour however showed a stable improvement in the resilience of the Nautical Chain. Therefore, Vanlaer et al. (2021) might underestimate the effect of the Nautical Chain, thus the position of the port authority in increasing the resilience might be less then Vanlaer et al. (2021) stated. Third, Abioye et al. (2021) also found that increasing speeds improves the resilience, but they found a small effect and conclude that it is not enough to be resilient from the lens of shipping companies. The results of our research however showed that increasing the average speed does improve the resilience from a Nautical Chain perspective. Due to the inclusion of the Nautical Chain, the increase in speeds in ports also lead to less piloting and towing time. Therefore, the services of the Nautical Chain can handle more vessels in the same time with increasing the average speed in port, increasing the effectiveness of this mitigation strategy. Last, Imai et al. (2003) show the debate on vessel priorities with congested ports. When the effect of the disruption is larger, and thus the port is more congested, it was found that the smallest vessel first vessel priority strategy yield best results, adding to the debate mentioned in Imai et al. (2003). The contributions of this research on the knowledge in the literature are thus the position of the terminal, the position of the port authority, the effectiveness of increasing speed and the debate on vessel priority strategies.

Practical implications

The practical implementation of the proposed mitigation strategies in ports is non-trivial. First, increasing the average speed with 20% in ports can impact the safety of the port. However, in the base-case the average speeds in port are between the minimum and maximum value, and the increase of this mitigation strategy results in speeds lower than the maximum. Second, when the vessel priority strategies provide benefits for vessels overall, certain vessels might encounter larger delays. This asks for a distribution of the costs and the benefits between the advantaged and disadvantaged vessels. Last, the capacity mitigation strategies ask for flexibility in the schedules of the pilot organisation and tugboat companies, possibly leading to costs for these organisations. Compensation might be needed to stimulate the organisations to have a flexible schedule. The practical concerns that arise with the implementation of the mitigations strategies concern the safety, distribution of costs and benefits and compensation.

Limitations of the research

Practical constraints limit the applicability of the results found in this research. First, some real-world phenomena are excluded, like the overtake and encounter rules in port. Also, the boatmen are not included since under normal functioning they are barely cause for delays. This might not be true with disruptions. Furthermore, there is only one tugboat company in the model, while in the Port of Rotterdam there are three tugboat companies active. Normally, shipping companies have contracts with one of these companies, adding extra complication to the implementation. Second, the set of mitigation strategies included in this research is not complete. Within the mitigation strategies, certain values have been chosen like an 20% speed increase and increasing with 3 and 6 pilots. Thereby, combinations of mitigation strategies have not been tested except for a simultaneous increase in pilots and tugs. Third, the financial impacts of the delays and mitigation strategies has not been included. Therefore, this research cannot provide insight in the possibilities for distributing the costs and the benefits. Last, this research is performed in a Port of Rotterdam case study. It is not known if the results found in this research are transferable to other ports with different characteristics. The limitations of this research thus might affect the applicability of the results found in this research.

8. Conclusions and Recommendations

This research aims to give insight in the current state of resilience of the Nautical Chain and look into mitigation strategies improving the resilience of the Nautical Chain. Ports are important for global supply chains, with over 80% of the global volume of trade transported through ports. Within ports, the Nautical Chain supports the turnarounds of vessels with piloting, towing and unloading. When one of the services of the Nautical Chain does not deliver, the whole port call process get disrupted, leading to delays for vessels. Therefore, the resilience of the Nautical Chain is critical for the resilience of ports, and thus the resilience of the supply chains.

To give insight in the current state and improvements to the resilience of the Nautical Chain, a literature review was performed and a DES model has been built for the Port of Rotterdam. The literature review resulted in insights in the concept of resilience, conceptualisation of the Nautical Chain and identification of disruptions. The DES model provided quantitative results on the current state of resilience of the Nautical Chain in five scenarios, and the effects of seven different mitigation strategies on this resilience.

This chapter is structured as followed: first the sub-questions will be answered separately, after which the main research question will be answered. Next, recommendations for further research will be given. This chapter ends with a policy advice for the port authority of the Port of Rotterdam on the mitigation strategies improving the resilience of the Nautical Chain.

Sub-question 1: How to define Nautical Chain resilience

Nautical Chain resilience is defined as the deviation of the average time in system of vessels from the business-as-usual value. The area under the resulting graph is the measurement of resilience, where two metrics have been identified defining this deviation: (1) the maximum deviation from the business-as-usual value and (2) the duration from the end of the disruption to get back to the business-as-usual value. Resilience could thus be improved by either decreasing the maximum average time in system or recovering to the business-as-usual value earlier. With the area under the graph, and the difference of this area when mitigation strategies are active, the resilience of the Nautical Chain can be measured and differences in this resilience can be quantified.

Sub-question 2: What kind of disruptions can be expected in ports?

It has been found that the following kinds of disruptions could be expected in ports: accidents, labour disputes, economic and geopolitical, ICT, water, weather, geophysical, climate change and pandemics. A selection was made, which resulted in the following disruptions being included in the experiments: Pandemic, Accident, Suez-Canal blockage, Weather and Cyber-Attack.

Sub-question 3: Which actors and processes determine the resilience of the Nautical Chain?

The following actors of the Nautical Chain have been included in this research:

- Vessel
- Pilot
- Pilot vessel
- Tugs

- Terminal
- Harbour master

With the inclusion of these actors, the following activities have been included:

- Boarding/deboarding pilot
- Connecting/disconnecting tugs
- Unloading
- Sailing
- Piloting
- Towing

Sub-question 4: How to model the Nautical Chain?

Discrete Event Simulation, Agent Based Modelling and Continuous modelling have been considered to model the Nautical Chain. DES is best suited to model the resilience of the Nautical Chain since the Nautical Chain system in ports can be seen as queuing system, with the organisations of the Nautical Chain as service stations. Also, this research focusses on the flow of vessels trough the Nautical Chain system, which is in line with the focus of the DES technique on the flow of items trough a system. Therefore, DES is identified to be best suited to model the Nautical Chain.

Sub-question 5: What is the current state of resilience of the Nautical Chain?

The DES model was constructed to measure the resilience of the Nautical Chain, where the average time in system of vessels determined the resilience. The results of the deviation of the average time in system for the five scenarios showed that not all disruptions equally impact the resilience of the Nautical Chain. The effects of the disruptions on the average time in system of vessels was largest for the cyber-attack, followed by the pandemic, accident, weather, and least for the Suez Canal blockage scenario.

Sub-question 6: Which strategies are recommended to improve the resilience of the Nautical Chain?

Seven different mitigation strategies have been tested, with four policy mitigation strategies and three capacity mitigation strategies. From the policy mitigation strategies, first increasing the average speed of vessels in port with 20% performed stable in improving the resilience in all scenario's. The vessel priority mitigation strategies yielded different results, with the smallest vessel fist strategy performing best overall. For the capacity mitigation strategies stable improvements to the resilience were found. Overall, increasing the amount of tugs performed worst in improving the resilience, while a simultaneous increase in pilots and tugs performed best of the capacity mitigation strategies. Overall, the simultaneous increase in pilots and tugs performed best of all mitigation strategies.

Summary of the conclusion answering the main research question: How to measure and improve the resilience of the Nautical Chain?

This research showed that improvements to the resilience of the Nautical Chain can be made by implementing mitigation strategies. The effect of this improvement differed for each scenario and each mitigation strategy. Starting with increasing the average speed with 20 %s in port the improvements were stable, and most improvement of the resilience was found in the Suez Canal Blockage scenario with an improvement of 21%, while the least improvement was found in the pandemic scenario with an improvement of 3.5%. Next, the largest vessel first vessel priority strategy showed different results, ranging from a decrease of the resilience of 19% to an increase of 5%. The less tugs first priority strategy results ranged from an decrease of 1% to an increase of 9%. The smallest vessel first priority strategy showed a decrease of 2% and a maximum increase of 14%. With regard to the capacity mitigation strategies, increasing the amount of pilots with 6 pilots resulted in a minimal increase of 1% and a maximum increase of 42% in the resilience of the Nautical Chain. Increasing the amount of tugs with 5 tugs resulted in a minimal increase of 2% and a maximum increase of 8%. However, the best results improving the resilience were achieved by a simultaneous increase in pilots and tugs with a minimum increase of 11% and a maximum increase of 46%. Therefore, the best policy mitigation strategy is increasing the average speed in port, and the best capacity mitigation strategy and overall the best strategy is the simultaneous increase of pilots and tugs.

Recommendations for further research

This research focussed on the resilience of the Nautical Chain and is applied on the Port of Rotterdam. For further research it would be interesting to apply this on other ports. By applying it to other ports, it can be seen if the results of this research also apply to other ports. By repeating the research for other ports, the findings of this report can be either generalized for all ports, or be found to be port specific.

Further research could also look into the position of the actors of the Nautical Chain on the proposed mitigation strategies. The mitigation strategies proposed in this research impact the actors of the Nautical Chain, leading to costs and benefits for different actors. The actors of the Nautical Chain could be interviewed about their position on the mitigation strategies, and the distribution of the costs and benefits inferred by implementing different strategies. An example of distributing costs and benefits can be found in the smallest vessel first strategy. It is shown that in some scenarios, the average time in system of all vessels in port is lower than with the base case, while larger vessels will occur larger delays and smaller vessels have the smallest delays. Compensation from the smallest vessels to the larger vessels distributing the costs and benefits is therefore necessary, while keeping in mind that overall all vessels benefit from this strategy. The position of the actors and scheme of distribution are thus a topic for further research.

Including more details in the scope within the ports could lead to a more accurate determination of the exact effects of mitigation strategies. It is not expected that the results found in this research and their magnitude will change, but the exact improvements could be estimated better with more details included. Research following this thesis could therefore look at including boatmen, where it would be interesting to see if boatmen are indeed barely cause for delays even during disruptions. Also, modelling the different tugboat companies would increase the level of detail with the different mitigation strategies. By adding more detail in the Nautical Chain the effects of the mitigation strategies can be more precise.

Last, this research showed the effect of different mitigation strategies on the average time in system of vessels in the port system. For further research, it might be interesting to see if mitigation strategies can steer the graph, and thus the average time in system, towards a certain goal. The port authority might want a maximum average time in system, and a maximum time to get back to the business-as-usual value. Further research might look into steering the graph towards certain goals.

8.1 Policy advice

This research concludes with a policy advice for the port authority of the Port of Rotterdam. The results of this research show that the Nautical Chain can provide contributions improving the resilience, thus decreasing the delays in ports caused by disruptions. It is therefore recommended to plan ahead for disruptions that might happen in the port, talking with the actors of the Nautical Chain to gain insight in their position towards the mitigation strategies. With these insights, plans can be made to implement mitigation strategies in a timely manner, and the compensation schemes distributing the costs and benefits between the actors can ensure the execution of the mitigation strategies. The mitigation strategies advisable to implement in the Port of Rotterdam are elaborated below, including advice on the actors to contact to prepare for implementing these mitigation strategies.

Average speed

Increasing the average speed in the port showed stable resilience improving results. Therefore, it is advised to have a meeting with the VTS, pilot organisation and tugboat companies discussing the possibilities of increasing the average speed in the port. With all these actors together, all knowledge is present to explore the possibilities in increasing the average speed in port without hindering safe operations in port, and how much the speed can be increased under different circumstances. The pilot organisation is, besides the VTS, the most important actor to get onboard with the plans. An agreement between these organisations can ensure a quick implementation of the increase in average speed in port after the disruption has happened.

Vessel priority strategies

The vessel priority strategy showed mixed results on the improvement of the resilience, therefore it is advised to have a meeting with the shipping companies (or their representatives) and terminals. Here, the outcomes of this research, especially during the cyber-attack scenario, can be discussed but also the ineffectiveness of these strategies in other scenarios should be discussed. The preferred vessel priority strategy is letting the smallest vessels in first, which is able to make the waiting times, and thus average time in system, over all vessels less in some scenarios. It should be made insightful that everybody, also the not affected terminals, benefit from such a strategy in this scenario. A compensation for the larger vessels could be negotiated, and budget could be created by the added value for shipping companies, who benefit from the shorter turnaround time. Only when this strategy is agreed upon, it should be implemented.

Capacity strategies

Considering all the capacity strategies, it was found that increasing both the amount of pilots and tugs yield the best overall results with regard to improving the resilience of the Nautical Chain. Therefore, this mitigation strategy should be discussed with the pilot organisation and tugboat companies. The benefits of implementing this strategy for the average time in system of vessel should be elaborated upon. The harbour master can negotiate for financial compensation for the extra tugs and pilots. Also, agreement on reducing the capacity of the pilot organisation and tugboat companies when a disruption is active, so that it can be increased when the disruption has passed should be discussed. The advantages on the resilience are so large, that this option should definitely be considered for implementation with disruptions.

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A. Conceptual model

A1. Assumptions and simplifications

Within the scope of the research, assumptions and simplification have to be made to reduce the system to be able to meet the modelling objectives. In A1.1, the main assumptions will be presented while in A1.2 the main simplifications will be presented.

A1.1 Assumptions

Besides the assumptions mentioned in the main text, the following (important) assumptions were made:

- Section speed is average between min- and max section speed
- A month has 30 days, so a month is 720 hours
- Arrival pattern is exponentially distributed with regard to the interarrival time
- When a vessel is created, first the class is set based on the distribution of classes in the whole port. Next, based on the amount of each class for each destination the destination is set. For each class:
    1.
        - Length uniform between 80 and 119
    2.
        - Length uniform rounded 120 200
    3. 31
        - Length uniform rounded 200 300
    4. 32
        - Length uniform rounded 200 300
    5. 4
        - Length uniform rounded 300 400
    6. 5
        - Length uniform rounded 300 400
    7. 6
        - Length uniform rounded 300 400
- Based on the destination and the class, the unload time is set
    1. In the unload time, all 0's have been updated with the value of the next largest class which is non zero
- No different companies for tugs, so every tug can handle every vessel
    1. With that, all mooring places can be used by all tugs
- Terminals
    1. MW has 4 mooring places
    2. RWG and APMT are one terminal
    3. TweedeWerkhaven and Pistoolhaven are one terminal
    4. Vessels take 1.1 * their length at length quays
    5. 1 hour prior to departure, the quay is released and can be occupied by another vessel

A1.2 Simplifications

Besides the simplifications mentioned in the main text, the following important simplifications were made:

- Boatmen excluded
- Some terminals excluded
- Waterinfrastructure rules not incooperated
- No difference between calling pilots from land station or sea station for incoming voyages (Balancing pilots)
- Tugs are based on class, not destination
- Only arrival data used

A2. Processes in the model

The model has very complex structures. The process of unloading vessels is depicted in the figure below for full insight in the functioning of the model.

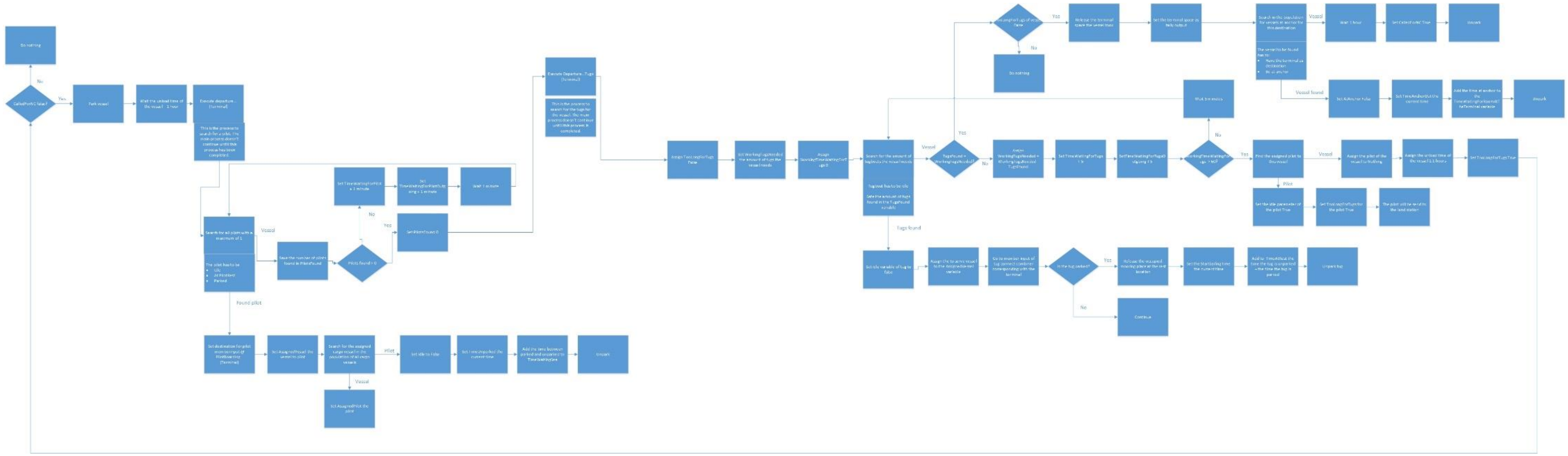


Figure A1: Detailed Overview Of Vessel Processes

B. Data

B1 Vessel data

Cargo vessels are the main object of study in this research. Therefore, a lot of data is used to set attributes of cargo vessels. The order of assigning these attributes is important, since certain attributes can only be set after another attribute is set previously. The attributes in this model, and the order of assigning them, is:

1. Class
2. Destination
3. Length
4. Draught
5. Tugs needed
6. Unload time

This is also the order in which the value of these attributes will be discussed.

B1.1 Vessel Class

First, the class of the vessel has to be set. The destination is dependent on the class, since not all classes go to all destinations in the port. Besides, the length, draught, amount of tugs needed and unload time are, at least partly, dependent on the class.

To assign a class to a vessel, the data of Verduijn (2017) have been aggregated. From the data of incoming vessels, the sum of all vessels incoming into the Port of Rotterdam is calculated, which gives the values given under Chance in Table B.1.

The class of the vessel will be randomly assigned, where the chance is dependent on the value in the chance column.

Due to constraints of the modelling program, the classes 3a and 3b are substituted for class 31 for 3a and class 32 for 3b in Table B.1.

Table B.1: Distribution of classes

	Class	Chance
1	1	1750
2	2	2062
3	31	685
4	32	89
5	4	154
6	5	21
7	6	19

B1.2 Vessel destination

Now that a vessel has a class, next the destination can be assigned. From the thesis of Verduijn (2017), the distribution of classes has been aggregated into Table B.2. This table shows for each destination the amount of vessels arriving for a period of two months. Choosing the vessel class, the destination is randomly assigned based on the amount of vessels going to each destination.

Table B.2: Vessel destination and occurrences per class

	Destination	Vessels Per Day	Class1	Class2	Class31	Class32	Class4	Class5	Class6
1	Calland	35,1	195	605	195	41	6	1	11
2	MOT	1,6	4	1	21	13	1	0	8
3	Petroleum6	1,6	7	29	6	5	0	0	0
4	ECTAmazone	8,1	15	111	44	21	48	5	0
5	EMOMissisippi	0,6	15	2	1	1	0	0	0
6	ECTEurope	5,4	18	37	86	0	21	0	0
7	APM	4,1	14	55	33	0	21	1	0
8	Euromaxx	3,9	12	74	0	0	25	5	0
9	MW	0,5	0	3	6	5	0	0	0
10	RWGAPMT	5,5	9	71	44	1	31	9	0
11	Petroleum3_1	3,4	55	46	1	0	0	0	0
12	Petroleum3_2	3,4	56	46	0	0	0	0	0
13	TweedeWerk...	1,7	49	33	4	0	0	0	0
14	Pistoolhaven	0	0	0	0	0	0	0	0
15	Botlek	6,4	126	62	4	0	0	0	0

B1.3 Vessel Length and Draught

In the thesis of Verduijn (2017), the length and draught of each vessel class is given in a range, which can be seen in Table B.3.

Table B.3: Length and draught for each vessel class (Verduijn, 2017)

Class	L [m]	T[m]
1	$<$120	
2	120-200	
3a	200-300	$<$14.3
3b	200-300	$>$14.3
4	$>$300	$<$14.3
5	$>$300	14.3-17.4
6	$>$300	$>$17.4

B1.4 Tugs needed

For the amount of tugs needed, the vessel class is used. Data from the thesis of Verduijn (2017) is aggregated to an amount of tugs for each vessel class. For every amount of tugs that is needed in that class, the occurrences are counted, leading to a chance that a certain vessel class need a certain amount of tugs. This can be seen in Table B.4 till Table B.10.

Table B.4: Tugs needed distribution for class 1

	Tugs	Chance
1	0	1652
2	1	70
3	2	27
4	3	1

Table B.5: Tugs needed distribution for class 2

	Tugs	Chance
1	0	1433
2	1	248
3	2	376
4	3	1
5	4	2

Table B.6: Tugs needed distribution for class 3a

	Tugs	Chance
1	0	312
2	1	93
3	2	263
4	3	13
5	4	4

Table B.7: Tugs needed distribution for class 3b

	Tugs	Chance
1	0	2
2	1	2
3	2	32
4	3	52
5	4	1

Table B.8: Tugs needed distribution for class 4

	Tugs	Chance
1	0	27
2	1	9
3	2	100
4	3	17
5	4	1

Table B.9: Tugs needed distribution for class 5

	Tugs	Chance
1	0	3
2	2	13
3	3	5

Table B.10: Tugs needed distribution for class 6

	Tugs	Chance
1	3	2
2	4	17

B1.5 Unload time

With the vessel class and the destination, the unload times for a vessel can be seen in Table B.11. This table contains aggregated data from the thesis of Verduijn (2017).

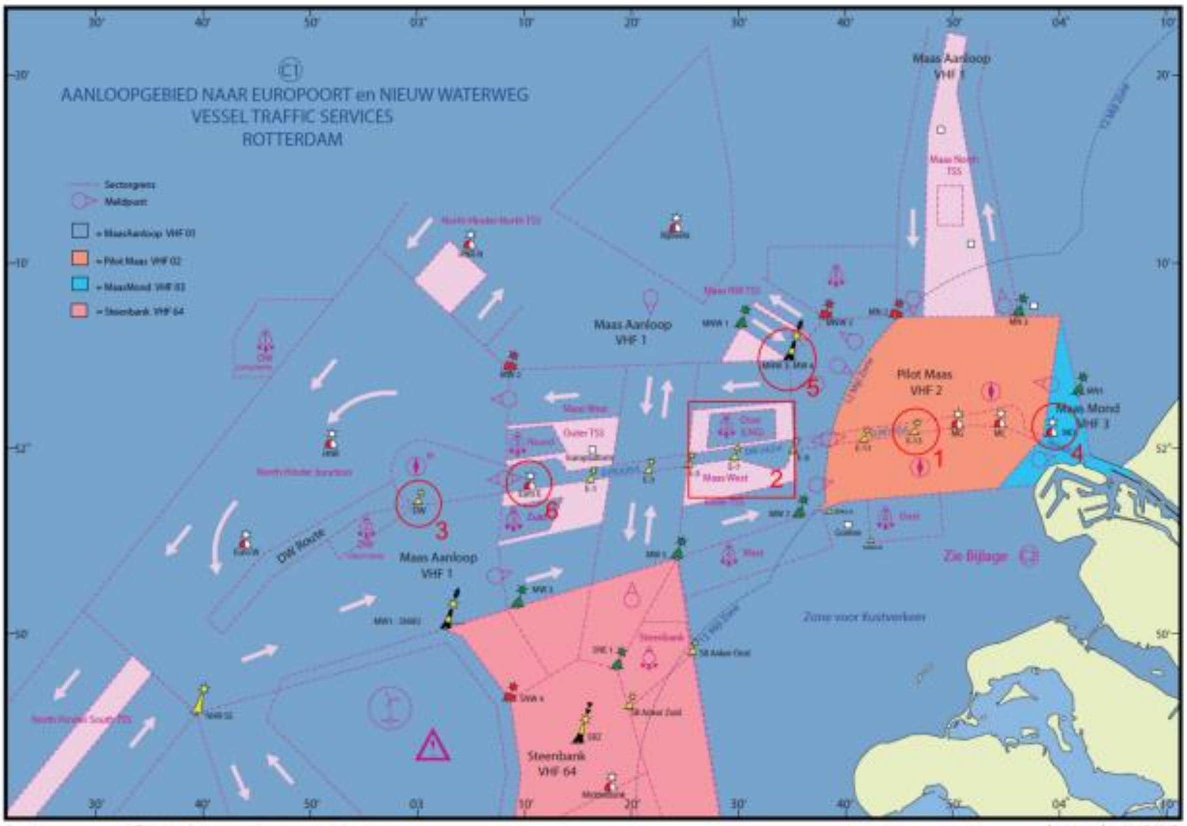
Table B.11: Unload times

	Destination	Class1	Class2	Class31	Class32	Class4	Class5	Class6
1	APM	10	10	10	10	18	18	18
2	RWGAPMT	5	10	10	10	19	19	19
3	Calland	6	11	11	11	19	19	19
4	ECTAmazone	10	10	10	10	18	18	18
5	ECTEurope	10	10	10	10	18	18	18
6	EMOMissisippi	10	10	10	10	17	17	17
7	Euromaxx	10	10	10	10	18	18	18
8	MOT	21	21	21	21	21	21	21
9	MW	5	10	10	10	19	19	19
10	Petroleum3_1	15	17	17	18	18	18	18
11	Petroleum3_2	15	17	17	18	18	18	18
12	Petroleum6	16	16	16	16	18	17	17
13	Pistoolhaven	16	16	18	18	20	20	21
14	TweedeWer...	15	17	17	18	18	18	18
15	Botlek	15	17	17	18	18	18	18

B2 Pilot data

Pilots are the entities that all vessels use in the scope of this model. These pilots guide the vessels from the port entrance to their berth in port, and from the berth back to the port entrance. In Figure B.1, there can be seen where the pilot boarding areas are. For incoming vessels, this is the location where the pilot boards the vessel. For outgoing voyages, the pilot boards the vessel at the terminal.

Besides the boarding locations, data on the time it takes to board and deboard the vessel are important. According to a system expert, Ms. Nikghadam, the boarding of a pilot takes 10 minutes.



 Laatste update 01-07-2017.

Figure B.1: Pilot boarding areas (Verduijn, 2017)

B3 Tug data

For the tugs in this model, data on the tug rendezvous locations, tug rest locations and tug connection time are needed.

First, following the thesis of Verduijn (2017), there are four tug rest locations in the Port of Rotterdam. These can be seen in Table B.12, with their respective sections. To determine the exact location of these rest locations, Google Earth has been used, where these locations have been found exactly. Each rest location has a fixed amount of mooring places, which is limited. The amount of mooring locations is determined by Google Earth . This resulted in the amount of mooring places given in Table B.13.

Table B.12: Tug rest locations (Verduijn, 2017)

Name	Section
Scheurhaven	8
4e PET	8
Tenessee-haven	11
Wilhelmina-haven	105

Table B.13: Mooring places per rest location

Name	Mooring places
Scheurhaven	12
4e PET	4
Tenessee-haven	4
Wilhelmina-haven	8

Next, the tug rendezvous locations have to be determined. This data is also gathered from the thesis of Verduijn (2017). There are 5 tug rendezvous locations, where this location depends on the destination terminal of the vessel. In Table B.14 the destination sections and corresponding rendezvous locations can be seen, and in Table B.15 the vessel destinations and rendezvous locations can be seen. The geographical locations of the western 4 tug rendezvous locations can be seen in Figure B.2. The Eastern 2 tug rendezvous locations can be seen in Figure B.3.

Table B.14: destinations and rendezvous locations (Verduijn, 2017)

	Destination section	Meeting section (approximate)
1	11 17 18 19 22 27 32 35 42 45 46 49 50 55 58 59 60	10
2	7	6
3	8	8
4	71 78 79 80 81 82 83 84 85 86 87 88 89 90	71
5	104 105	78

Table B.15: Vessel destinations and rendezvous locations

Tug rendezvous location name	Vessel destination
Maasvlakte	MW RWGAPMT Euromaxx MOT Petroleum6 APM ECTEurope ECTAmazone EMOMissisippi
Calland	Calland
Maas	TweedeWerkhaven Botlek Petroleum3_1 Petroleum3_2

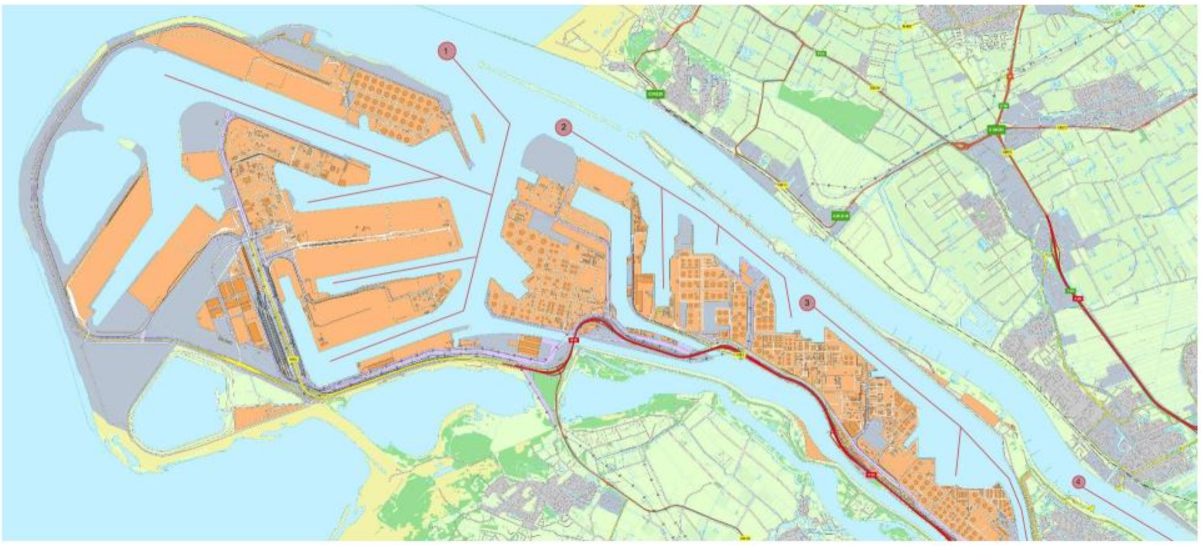


Figure B.2: Tug connection locations west (Verduijn, 2017)

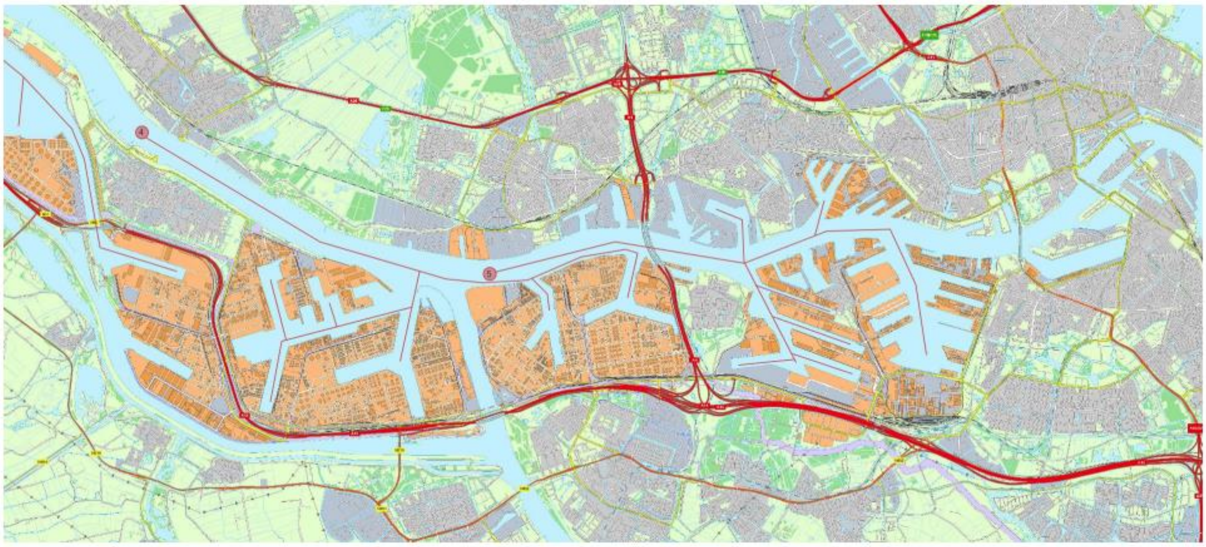


Figure B.3: Tug connection locations east (Verduijn, 2017)

B4 Terminal Data

For the terminals, within the scope, the only relevant data considers the unload time for each class at the terminal. In the thesis of Verduijn (2017), the unload times per terminal have been given. This can be seen in Table B.16. This data has been aggregated to correspond with the terminal present in the model, of which the result can be seen in Table B.17.

Table B.16: Loading and unloading times for each terminal (Verduijn, 2017)

Terminal	Section	Class 1	2	3a	3b	4	5	6
Hoek van Holland Stena	5	6:00	6:00	6:00				
Shtandart Noord Berth	7		15:31	17:49	17:49		19:42	
Caland	8	6:00	11:00	11:00	11:00	19:00	19:00	
MV1 - Gate	11							
MV1 - MOT	11			21:00		21:00	21:00	21:00
Tennesseehaven	11		15:31	17:49	17:49		19:42	5:38
Indorama	11	10:00	10:00					
BP	19	16:00	16:00	16:00	16:00	18:00	17:00	
MV1 - ECT Delta Amazonehaven	22		10:00	10:00	10:00	18:00	18:00	
MV1 - EMO Amazonehaven	22	10:00	10:00	10:00	10:00		17:00	17:00
MV1 - Brammernterminal Steinweg	27	6:00	11:00	11:00	11:00			
MV1 - EMO Mississippihaven	27	10:00	10:00	10:00	10:00	17:00	17:00	
MV1 - ECT Delta Europahaven	32		10:00	10:00	10:00	18:00	18:00	
MV1 - Rhenus Logistics	32		5:00	5:00	5:00			
MV1 - APMT Rotterdam	35		10:00	10:00	10:00	18:00	18:00	
MV1 - Lyondell	35	12:00	16:00	16:00				
MV1 - Euromax	42	10:00	10:00	10:00	10:00	18:00	18:00	
MV2 - Euromax	46	5:15	10:20	10:20	10:20	18:30	18:30	
MV2 - T3 west	50	5:15	10:20	10:20	10:20	18:30	18:30	0:00
MV2 - T3 oost	50	5:15	10:20	10:20	10:20	18:30	18:30	0:00
MV2 - SIF	55	5:15	10:20	10:20	10:20	18:30	18:30	0:00
MV2 - APMT (T1)	60	5:15	10:20	10:20	10:20	18:30	18:30	0:00
MV2 - RWG (T2)	60	5:15	10:20	10:20	10:20	18:30	18:30	
1e werkhaven	78	15:00	16:40	16:40	18:20			
3e PET centraal	79	15:00	16:40	16:40	18:20			
3e PET noord	80	15:00	16:40	16:40	18:20			
3e PET zuid-oost	81	15:00	16:40	16:40	18:20			
3e PET zuid-west	82	15:00	16:40	16:40	18:20			
Botlek centrale geul oost	83	15:00	16:40	16:40	18:20			
Botlek centrale geul 2e WH	84	15:00	16:40	16:40	18:20			
2e Werkhaven	85	15:00	16:40	16:40	18:20			
Botlek centrale geul TH	86	15:00	16:40	16:40	18:20			
Botlek centrale geul west	87	15:00	16:40	16:40	18:20			
Sint Laurenshaven	88	15:00	16:40	16:40	18:20			
Chemiehaven	89	15:00	16:40	16:40	18:20			
Botlek West	90	15:00	16:40	16:40	18:20			
Stad	105	7:38	12:38	12:33	12:33	20:33		
Achterland/Transit	105	0:00	0:00	0:00				

Table B.17: Unloadtimes aggregated for relevant terminals

	Destination	Class1	Class2	Class31	Class32	Class4	Class5	Class6
1	APM	10	10	10	10	18	18	18
2	RWGAPMT	5	10	10	10	19	19	19
3	Calland	6	11	11	11	19	19	19
4	ECTAmazone	10	10	10	10	18	18	18
5	ECTEurope	10	10	10	10	18	18	18
6	EMOMissisippi	10	10	10	10	17	17	17
7	Euromaxx	10	10	10	10	18	18	18
8	MOT	21	21	21	21	21	21	21
9	MW	5	10	10	10	19	19	19
10	Petroleum3_1	15	17	17	18	18	18	18
11	Petroleum3_2	15	17	17	18	18	18	18
12	Petroleum6	16	16	16	16	18	17	17
13	Pistoolhaven	16	16	18	18	20	20	21
14	TweedeWer...	15	17	17	18	18	18	18
15	Botlek	15	17	17	18	18	18	18

Terminal quay data

The quay data either consists of length or mooring places. The amount of either of those is determined by using Google Earth. The method of gathering this data will be explained, with first the length data.

To determine the length of a certain terminal, the measurement tool in Google Earth has been used. This can be seen in Figure B.4. The yellow line marks the length of the terminal.

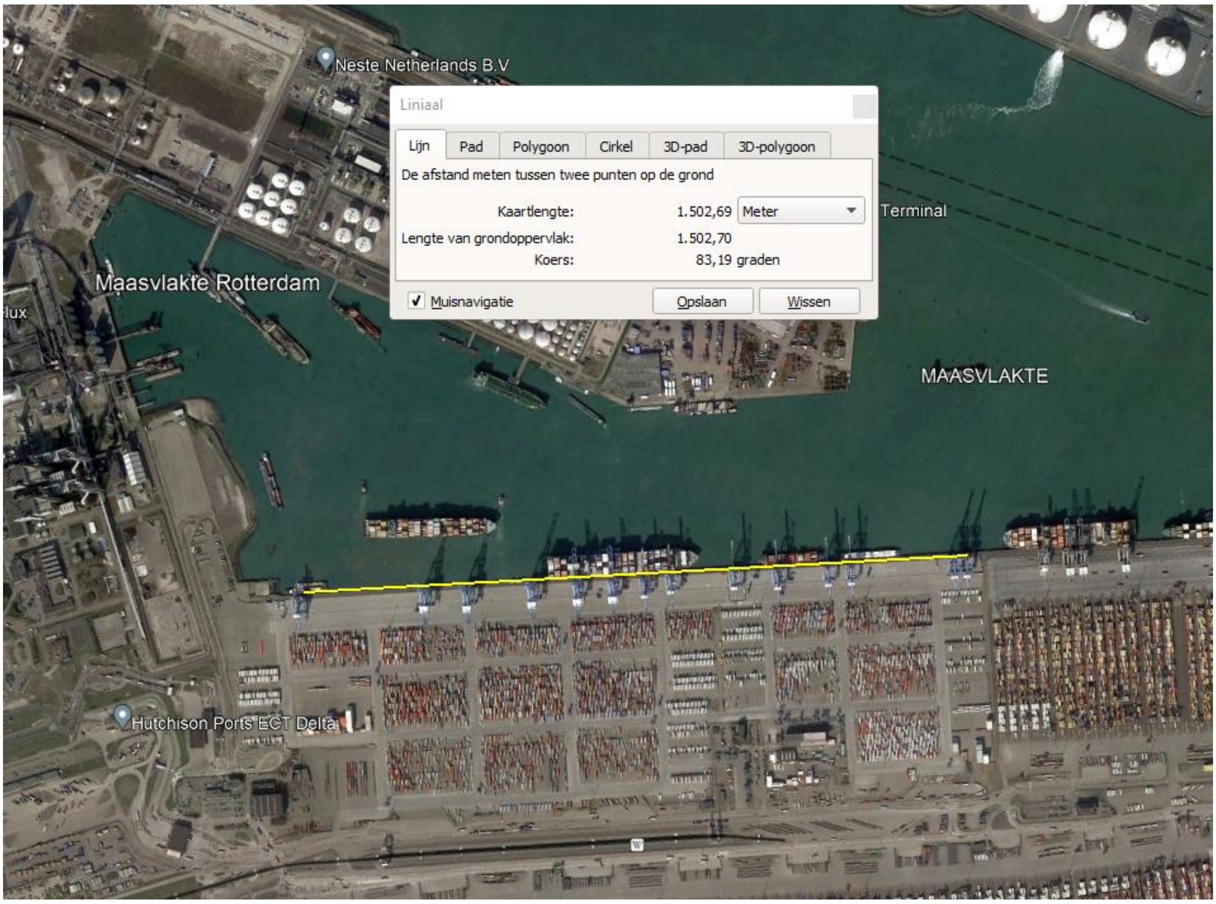


Figure B.4: Measuring terminal length

The amount of mooring places can be seen in table B.18. The method of retrieving these mooring places value is done by visual inspection in Google Earth. This can be seen in figure B.5 for the Petroleum 6 terminal.

Table B.18: Mooring places and terminal length

Terminal	*Mooring places or Length*	*Places or length*
Calland	Mooring places	62
MOT	Mooring places	4
Petroleum6	Mooring places	9
ECTAmazone	Length	2000
EMOMissisippi	Length	1800
ECTEurope	Length	1000
APM	Length	1000
Euromaxx	Length	1400
MW	Mooring places	4
RWGAPMT	Length	2200
Petroleum3_1	Mooring places	11
Petroleum3_2	Mooring places	11
TweedeWerkhaven	Mooring places	15
Botlek	Mooring places	22

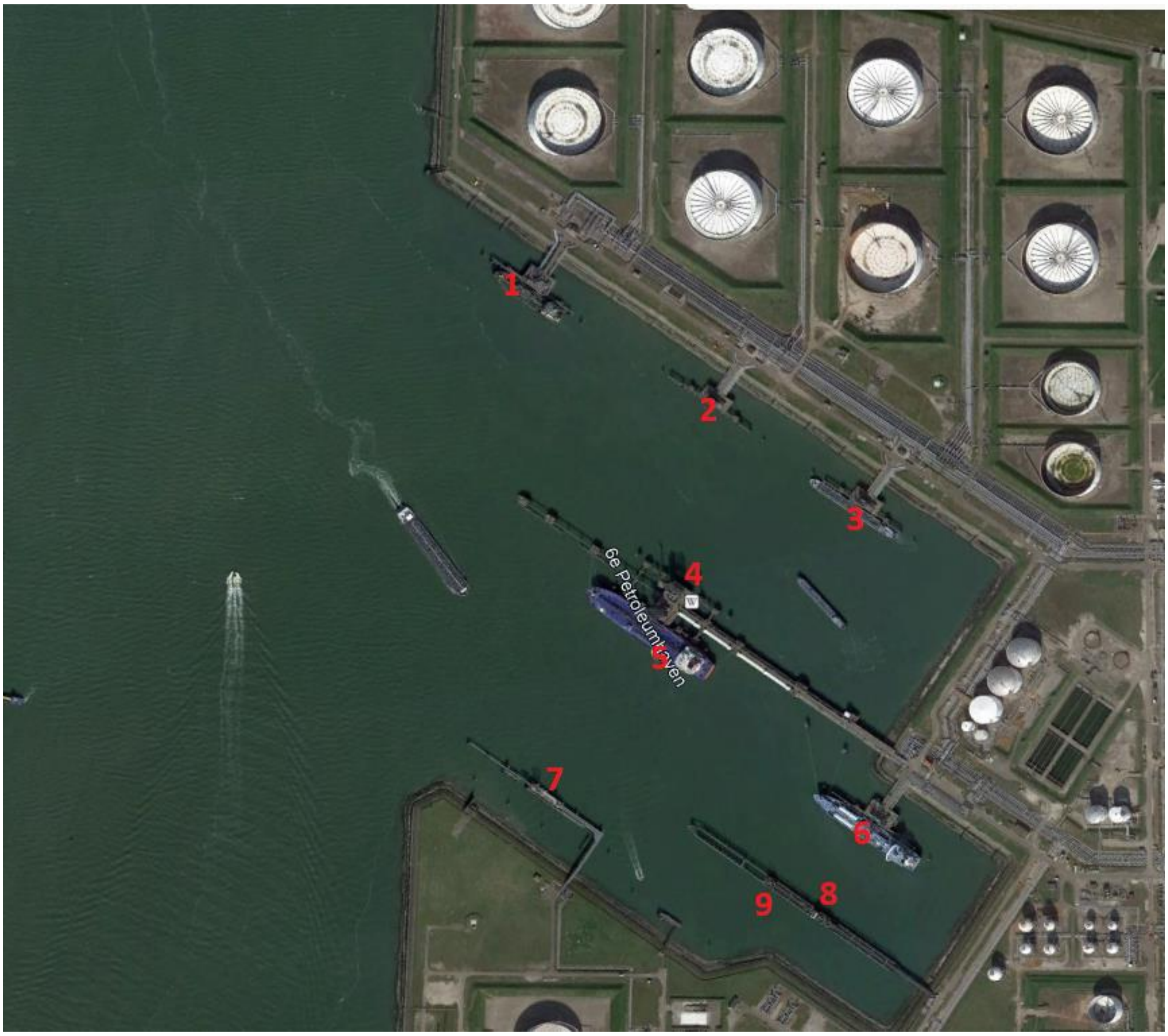


Figure B.5: Measuring mooring places

B5 Section speed data

The data regarding the allowed speeds of vessels on sections, dependent on their class, derived from the thesis of Verduijn (2017) can be seen in Table B.19. This data has been aggregated to be the average between the minimum and maximum speed values, which can be seen in Table B.20.

Table B.19: Section speeds per class (Verduijn, 2017)

Section	Class 1		2		3a		3b		4		5		6	
	Min.[kn]	Max.[kn]												
1		15		15		15		15		15		15		10
2	8	15	8	15	8	15	8	15	8	15	8	15	5	10
3	8	15	8	15	6	12	5	12	5	12	5	12	5	8
4	6	15	6	15	6	12	5	11	5	11	5	12	4	8
5	6	12	6	12	6	12	5	11	5	11				
6	4	10	4	10	4	6	4	6	3	5	3	5	1	4
7		10		10		6		6		5		5		4
8		8		8		6		6		4		4		3
10	4	8	4	8	4	6	4	6	3	5	3	5	1	4
11	4	6	4	6	2	4	2	4	2	4	2	4	1	3
17	4	6	3	5	2	4	2	4	2	4	2	4	1	3
18	4	6	3	5	2	4	2	4	2	4	2	4	1	3
19	4	6	3	5	2	4	2	4	2	4	2	4	1	3
22	2	3	2	3	2	3	2	3	1	2	1	2		
27	2	4	2	4	4	4	4	4	2	4	2	4	1	2
32	3	5	3	5	3	5	3	5	1	3	1	3		
35	3	5	3	5	3	3	3	3	1	3	1	3		
42	1	7	1	7	4	6	4	6	3	6	3	6		
45	4	4	4	4	4	3	4	3	3	3	3	3		
46	4	5	4	5	3	5	3	5	3	5	3	5		
49	3	4	3	4	2	3	2	3	2	3	2	3		
50	3	4	3	4	2	3	2	3	2	3	2	3		
55	3	4	3	4	3	4	3	4	2	3	2	3		
59	3	4	3	4	3	4	3	4	2	3	2	3		
60	3	4	3	4	2	3	2	3	2	3	2	3		
70	4	12	4	11	4	11	4	11	4	10				
71	4	12	4	10	4	10	4	9	4	8				
78	4	7	3	4	3	4	3	4		3				
79	4	6	3	4	3	4	3	4						
80	4	4	3	3	3	3	3	3	3					
81	4	4	3	3	3	3	3	3	3					
82	4	4	3	3	3	3	3	3	3					
83	4	6	3	4	3	4	3	4	3	3				
84	4	6	3	4	3	4	3	4	3	3				
85	4	6	3	3	3	3	3	3	3	3				
86	4	6	3	4	3	4	3	4		3				
87	4	4	3	3	3	3	3	3		3				
88	4	4		3	3	3	3	3		3				
89	4	4		3		3		3						
90		3		3		3		3						
91		10		3		3		3						
92		12												
100	4		3		3		3							
104		11		8		8		7		6				
105		6		4		4		4		3				

Table B.20: Aggregated data on section speeds per class

	Class						
Section	1	2	3a	3b	4	5	6
1	15	15	15	15	15	15	10
2	11,5	11,5	11,5	11,5	11,5	11,5	7,5
3	11,5	11,5	9	8,5	8,5	8,5	6,5
4	10,5	10,5	9	8	8	8,5	6
5	9	9	9	8	8	8	8
6	7	7	5	5	4	4	2,5
8	8	8	6	6	4	4	3
10	6	6	5	5	4	4	2,5
18	5	4	3	3	3	3	2
22	2,5	2,5	2,5	2,5	1,5	1,5	
27	3	3	4	4	3	3	1,5
32	4	4	4	4	4	2	
35	4	4	3	3	2	2	
42	4	4	5	5	4,5	4,5	
46	4,5	4,5	4	4	4	4	
50	3,5	3,5	2,5	2,5	2,5	2,5	
55	3,5	3,5	3,5	3,5	2,5	2,5	
60	3,5	3,5	2,5	2,5	2,5	2,5	
70	8	7,5	7,5	7,5	7		
71	8	7	7	6,5	6		
79	5	3,5	3,5	3,5			
81	4	3	3	3	3		
82	4	3	3	3	3		
83	5	3,5	3,5	3,5	3		
85	5	3	3	3	3		
88	4	3	3	3	3		
89	4	3	3	3			
90	3	3	3	3			
91	10	3	3	3			
92	12						
104	11	8	8	7	6		
105	6	4	4	4	3		

B6 Calibration

B6.1. Calibration section speed

Calibration of the turn-around time of vessels for different terminals and different classes has been performed. In the section below, the results of this calibration are shown for the tested section speeds. This starts with 0,9 followed by 1 and 1,1. For each of these section speeds, the aggregated percentual deviation is given as the individual values for the different classes at different locations. There has been chosen to go for a section speed of 1.1.

Table B.21: Section speed 0.9 summarized

Vessel Class	1	2	31	32	4	5	6	Total
Calibration value	1,22	1,38	1,48	1,40	1,47	1,65	1,60	1,46
Percentual deviation in model (1.1)	-18,61%	-20,25%	-9,70%	-13,24%	-36,97%	-4,15%	4,62%	-14,04%

Table B.22: Section speed 0.9 per terminal

	1	2	31	32	4	5	6
Calland	0,40	10,73	-0,36	-2,94	13,23	32,77	-17,65
MOT	59,29	35,71	19,98	4,27	-99,71		26,89
Petroleum6	-0,13	-11,30	12,83	-19,70			
ECTAmazone	-53,93	-50,94	-28,37	-21,76	-54,68	-59,33	
EMOMissisippi	-43,03	-16,26		-3,38			
ECTEurope	-20,25	-22,92	-22,54		-51,51		
APM	-2,05	-24,05	-20,70		-30,46		
Euromaxx	-39,42	-36,69			-16,99	40,48	
MW		-42,29	-23,14	-10,69			
RWGAPMT	-73,78	-53,91	-35,40	-38,51	-18,66	-34,68	
Petroleum3_1	-21,43	-24,90	13,48				
Petroleum3_2	-20,00	-23,41					
TweedeWerkhaven	-10,83	-11,81	-0,54				
Botlek	-16,70	-11,54	-21,97				

Table B.23: Section speed 1 summarized

Vessel Class	**1**	**2**	**31**	**32**	**4**	**5**	**6**	**Total**
Calibration value	1,22	1,38	1,48	1,40	1,47	1,65	1,60	1,46
Percentual deviation in model (1.1)	-10,79%	-12,11%	-0,92%	-2,40%	-27,20%	3,01%	12,94%	-5,35%

Table B.24: Section speed 1 per terminal

	1	2	31	32	4	5	6
Calland	8,16	19,24	8,62	9,32	24,71	40,45	-9,20
MOT	63,89	41,13	27,51	17,74	-93,57		35,09
Petroleum6	6,40	-2,85	21,41	-12,31			
ECTAmazone	-45,78	-42,29	-19,17	-9,66	-44,94	-50,31	
EMOMissisippi	-34,93	-8,59		0,93			
ECTEurope	-13,42	-15,44	-12,83		-41,08		
APM	5,83	-15,49	-11,11		-20,48		
Euromaxx	-31,45	-27,76			-6,93	47,36	
MW		-34,04	-12,98	1,44			
RWGAPMT	-65,60	-45,11	-25,18	-24,29	-8,14	-25,47	
Petroleum3_1	-12,50	-16,49	22,03				
Petroleum3_2	-11,32	-15,25					
TweedeWerkhaven	-1,82	-3,58	6,34				
Botlek	-7,67	-3,07	-14,76				

Table B.25: Section speed 1.1 summarized

Vessel Class	1	2	31	32	4	5	6	Total
Calibration value	1,22	1,38	1,48	1,40	1,47	1,65	1,60	1,46
Percentual deviation in model (1.1)	-3,98%	-5,88%	4,80%	2,75%	-22,00%	7,11%	19,28%	0,30%

Table B.26: Section speed 1.1 per terminal

	1	2	31	32	4	5	6
Calland	14,67	25,11	14,17	13,14	27,66	47,13	-2,19
MOT	68,97	44,79	32,45	21,34	-91,24		40,75
Petroleum6	12,30	1,46	26,40	-11,50			
ECTAmazone	-38,76	-36,01	-12,38	-4,95	-39,03	-44,82	
EMOMissisippi	-28,51	-2,19		19,39			
ECTEurope	-7,18	-9,42	-7,60		-36,29		
APM	12,34	-9,20	-5,06		-12,55		
Euromaxx	-24,55	-21,60			-1,71	52,52	
MW		-25,70	-8,92	5,45			
RWGAPMT	-58,35	-37,50	-17,97	-23,63	-0,82	-19,29	
Petroleum3_1	-4,72	-10,36	27,95				
Petroleum3_2	-3,68	-8,58					
TweedeWerkhaven	5,70	3,13	13,12				
Botlek	0,05	3,79	-9,37				

B6.2. Calibration pilots and tugs

The amount of tugs and pilots for the base case have to be determined. Therefore, the amount of pilots has been differentiated between 16 and 20, and with each of these pilot variations the tugs have been varied from 7 till 15. The results of these tests can be found in table B.27 till B.31.

First, the point where the waiting times stabilize has been determined. Next, together with an expert the most plausible value has been determined. This resulted in 17 pilots and 10 tugs for the base case.

Table B.27: Results of 16 pilots

	Average time waiting for pilots	Average time waiting for tugs
7 tugs	92,4511	13,239
8 tugs	33,5836	6,31548
9 tugs	23,6188	3,0943
10 tugs	20,6981	1,49523
11 tugs	19,8035	0,811464
12 tugs	18,8802	0,396783
13 tugs	18,8524	0,199956
14 tugs	19,0584	0,0939183
15 tugs	19,0636	0,0417191

Table B.28: Results of 17 pilots

	Average time waiting for pilots	Average time waiting for tugs
7 tugs	82,3092	14,2774
8 tugs	23,7115	6,59213
9 tugs	15,1109	3,31004
10 tugs	12,756	1,66273
11 tugs	11,8246	0,879143
12 tugs	11,1904	0,430833
13 tugs	11,2042	0,237998
14 tugs	11,2344	0,113888
15 tugs	11,1734	0,050297

Table B.29: Results of 18 pilots

	Average time waiting for pilots	Average time waiting for tugs
7 tugs	73,1228	14,9456
8 tugs	18,9828	6,94782
9 tugs	9,82725	3,44595
10 tugs	7,94184	1,76253
11 tugs	7,13985	0,919663
12 tugs	6,72116	0,476989
13 tugs	6,67056	0,254844
14 tugs	6,6914	0,126484
15 tugs	6,65556	0,0547469

Table B.30: Results of 19 pilots

	Average time waiting for pilots	Average time waiting for tugs
7 tugs	72,6433	15,6566
8 tugs	14,3555	7,18015
9 tugs	6,97616	3,58216
10 tugs	4,97702	1,80978
11 tugs	4,40354	0,975488
12 tugs	4,06496	0,508381
13 tugs	4,02018	0,277934
14 tugs	4,0159	0,136165
15 tugs	3,98106	0,063603

Table B.31: Results of 20 pilots

	Average time waiting for pilots	Average time waiting for tugs
7 tugs	59,7384	16,1174
8 tugs	12,7704	7,45707
9 tugs	5,02895	3,69122
10 tugs	3,34754	1,90244
11 tugs	2,80235	1,01427
12 tugs	2,49026	0,529157
13 tugs	2,44174	0,295211
14 tugs	2,44121	0,143296
15 tugs	2,42572	0,0706248

C. Experimentation

Here, all outcomes of all experiments have been included for full reference.

Table C.1: All outcomes of the Accident and Cyber-Attack scenarios

	Accident					Cyber Attack				
	Average time in system	Maximum time in system	Time back to normal	Area under graph	Percentual difference from base-case	Average time in system	Maximum time in system	Time back to normal	Area under graph	Percentual difference from base-case
Base case	15,63	55,90	509	5368		87,44	341,91	1246	155388	
Faster Section Speed	14,93	55,92	467	4776	-11,03%	75,97	331,69	1090	132594	-14,67%
Largest Vessel First	16,81	56,32	550	6380	18,85%	83,54	271,31	1317	147580	-5,02%
Less Tugs First	15,70	55,93	507	5430	1,15%	80,59	259,13	1436	141636	-8,85%
Smallest Vessel First	15,73	56,07	505	5463	1,76%	76,74	253,56	1304	133734	-13,94%
20 Pilots	14,86	55,95	479	4668	-13,04%	70,82	324,60	1044	122141	-21,40%
23 Pilots	14,57	55,92	472	4416	-17,73%	64,68	312,04	1006	109892	-29,28%
12 Tugs	15,49	55,99	516	5174	-3,61%	83,92	338,87	1213	148397	-4,50%
15 Tugs	15,33	55,64	507	5115	-4,71%	84,15	337,68	1231	148828	-4,22%
23 Pilots And 15 Tugs	14,15	55,68	467	4096	-23,69%	59,22	305,59	943	99157	-36,19%

Table C.2: All results of the Suez Canal blockage and Pandemic scenarios

	Suez Canal Blockage					Pandemic				
	Average time in system	Maximum time in system	Time back to normal	Area under graph	Percentual difference from base-case	Average time in system	Maximum time in system	Time back to normal	Area under graph	Percentual difference from base-case
Base case	9,76	15,21	509	261		23,69	78,04	1145	27203	
Faster Section Speed	9,68	14,56	488	206	-21,03%	23,04	78,32	1100	26250	-3,50%

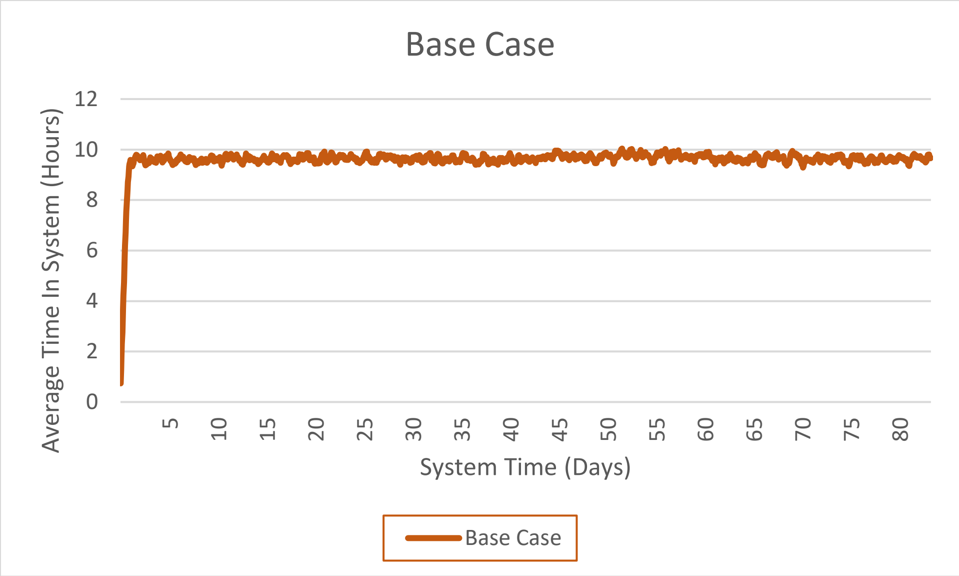
Largest Vessel First	9,77	15,16	509	262	0,44%	24,42	76,09	1150	28518	4,83%
Less Tugs First	9,76	15,19	509	260	-0,37%	22,98	76,34	1158	25770	-5,27%
Smallest Vessel First	9,76	15,19	509	260	-0,49%	22,57	75,25	1136	24948	-8,29%
20 Pilots	9,72	14,53	491	204	-21,82%	23,56	77,65	1188	26939	-0,97%
23 Pilots	9,67	14,40	486	189	-27,64%	23,69	78,01	1149	27006	-0,72%
12 Tugs	9,79	15,00	505	249	-4,86%	22,74	76,54	1123	25614	-5,84%
15 Tugs	9,75	15,02	509	250	-4,13%	22,45	77,24	1129	25030	-7,99%
23 Pilots And 15 Tugs	9,65	14,21	480	175	-30,20%	22,04	76,72	1049	24210	-11,00%

Table C.3: All results of the Weather scenario

	Weather				
	Average time in system	Maximum time in system	Time back to normal	Area under graph	Percentual difference from base-case
Base case	13,44	36,13	491	3350	
Faster Section Speed	12,74	35,01	489	2733	-18,41%
Largest Vessel First	13,48	36,03	508	3416	1,99%
Less Tugs First	13,46	36,02	491	3369	0,56%
Smallest Vessel First	13,42	36,04	491	3345	-0,14%
20 Pilots	12,41	34,22	489	2314	-30,93%
23 Pilots	12,00	33,52	344	1957	-41,59%
12 Tugs	13,23	35,62	491	3163	-5,57%
15 Tugs	13,34	35,44	493	3280	-2,07%
23 Pilots And 15 Tugs	11,92	33,15	333	1799	-46,30%

C1. Base case outcomes

Figure C.1: Results on Base Case



C2. Accident outcomes

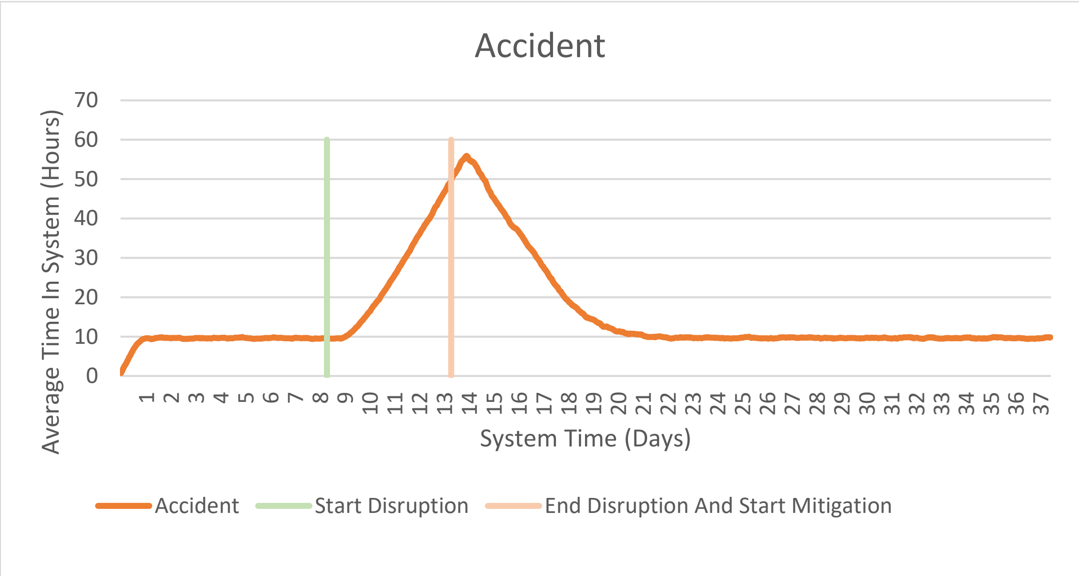


Figure C.2: Results of Accident on the base case

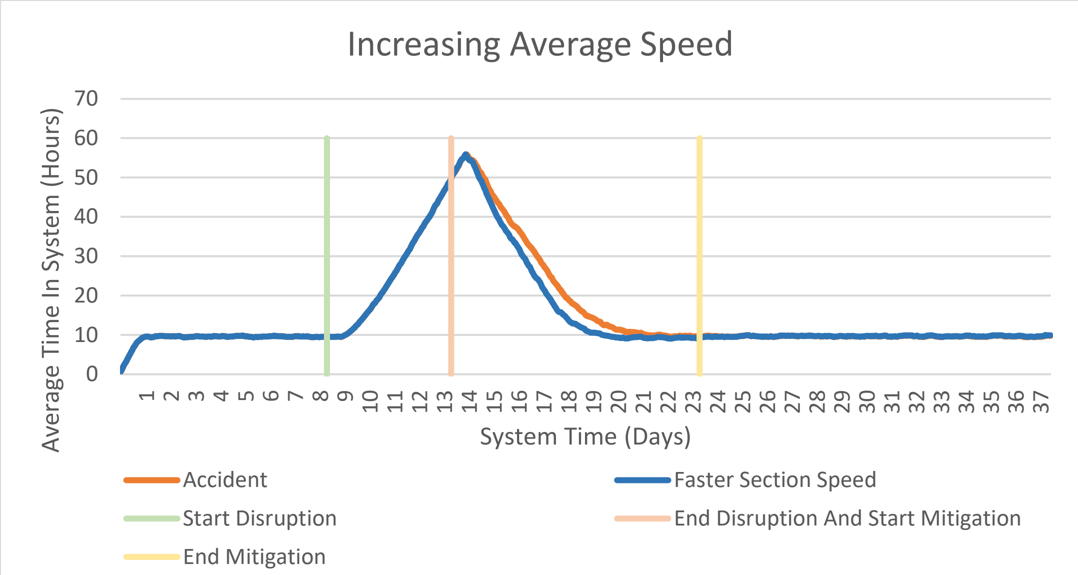


Figure C.3: Results of increasing the average speed with an accident

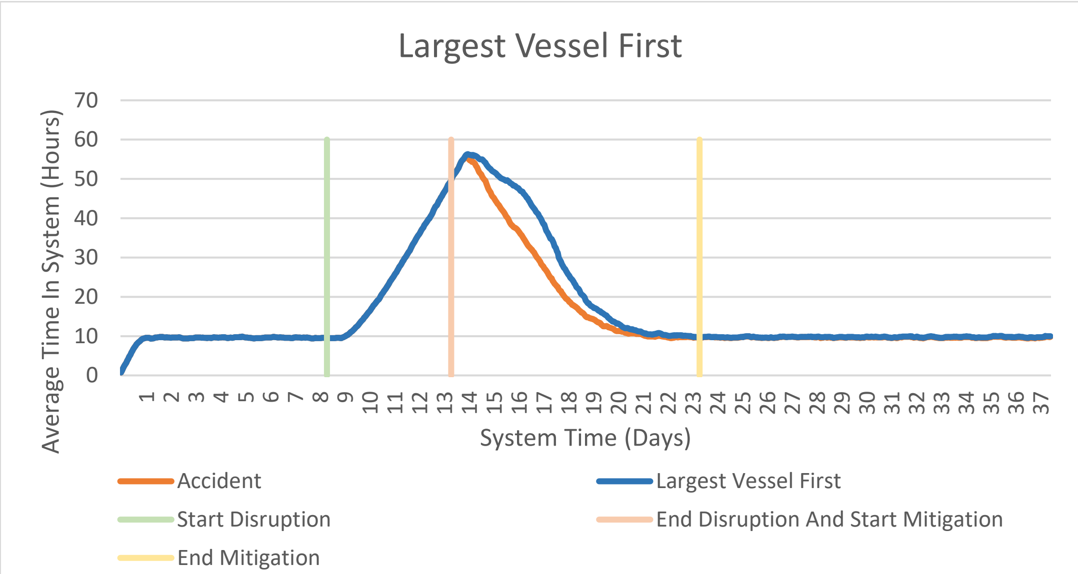


Figure C.4: Results of largest vessel first with an Accident

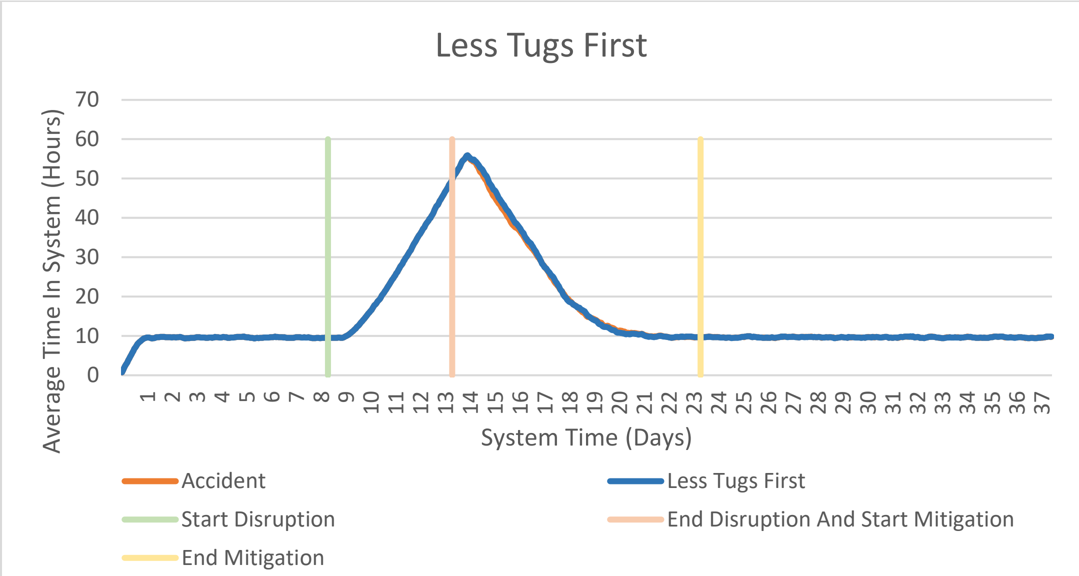


Figure C.5: Result of less tugs first on an accident

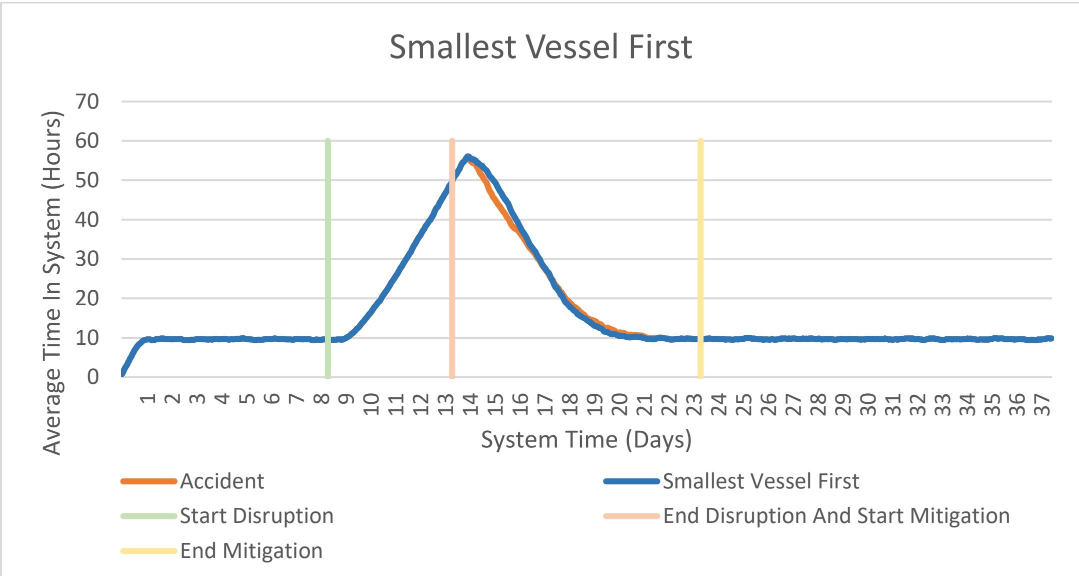


Figure C.6: Results of smallest vessel first with an accident

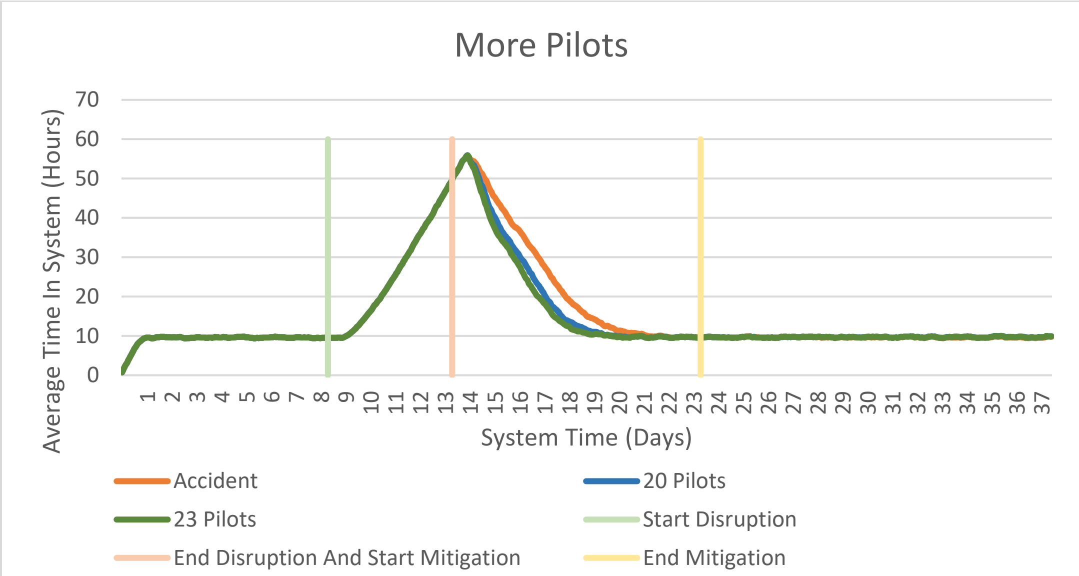


Figure C.7: Results of increasing pilots with an accident

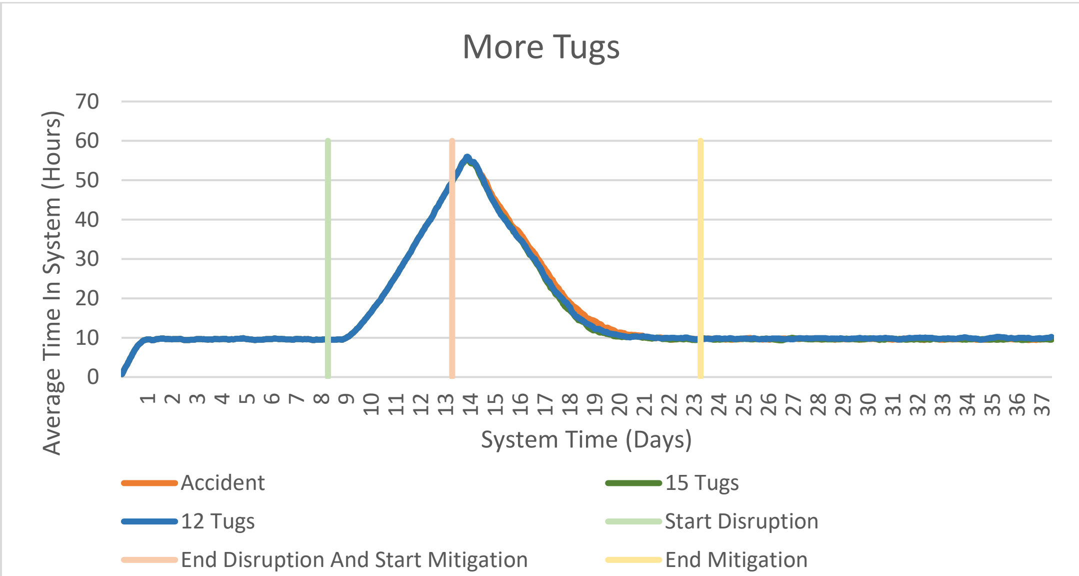


Figure C.8: Results of increasing tugs with an accident

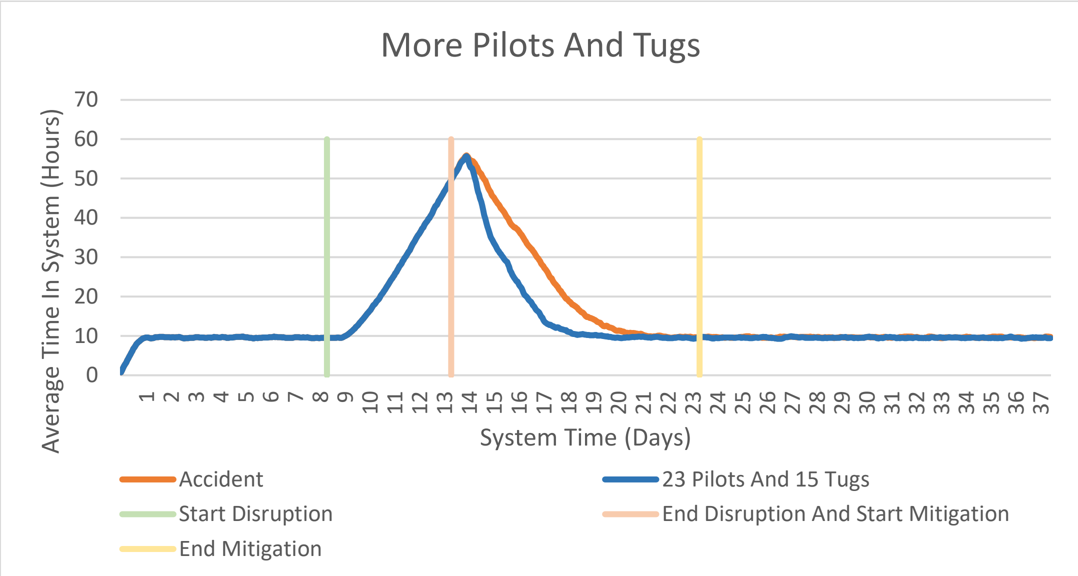


Figure C.9: Results of a simultaneous increase in pilots and tugs with an accident

C3. Cyber-Attack outcomes

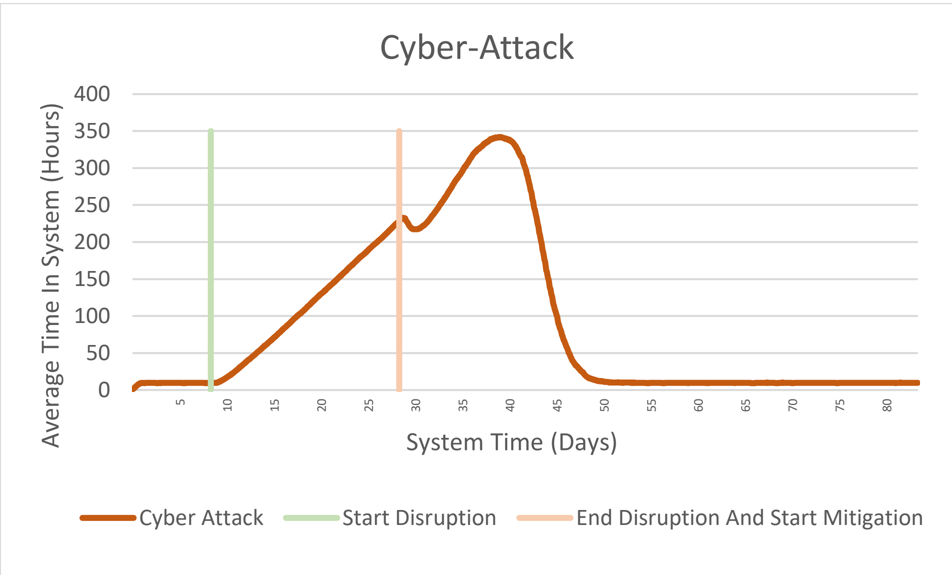


Figure C.10: Results of an cyber-attack on the base-case

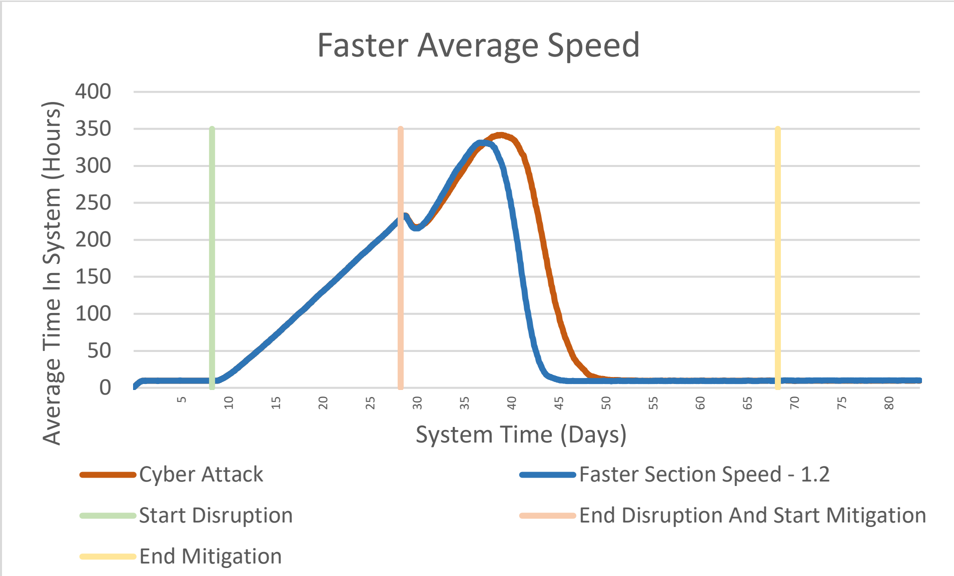


Figure C.11: Result of increasing average speed with an cyber-attack

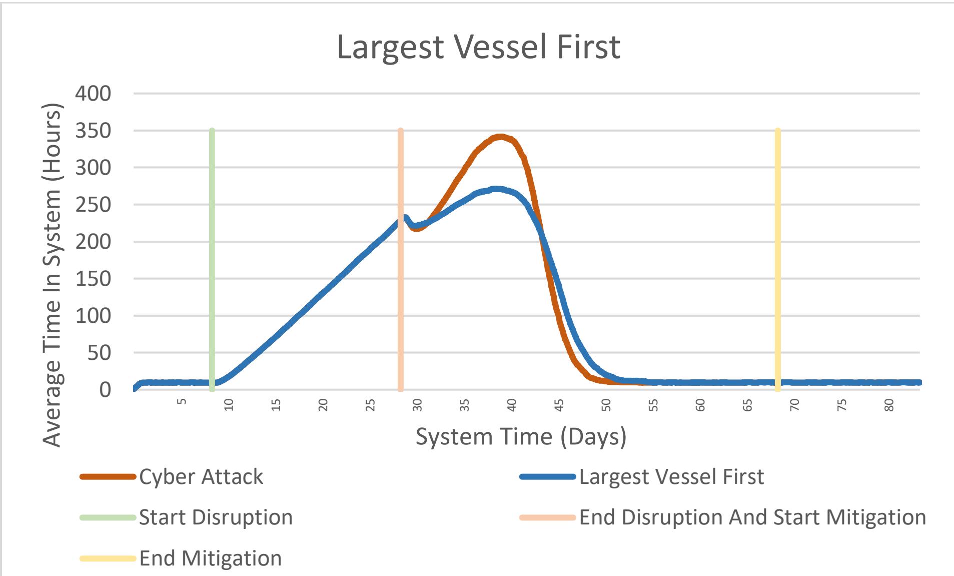


Figure C.12: Result of largest vessel first with an cyber-attack

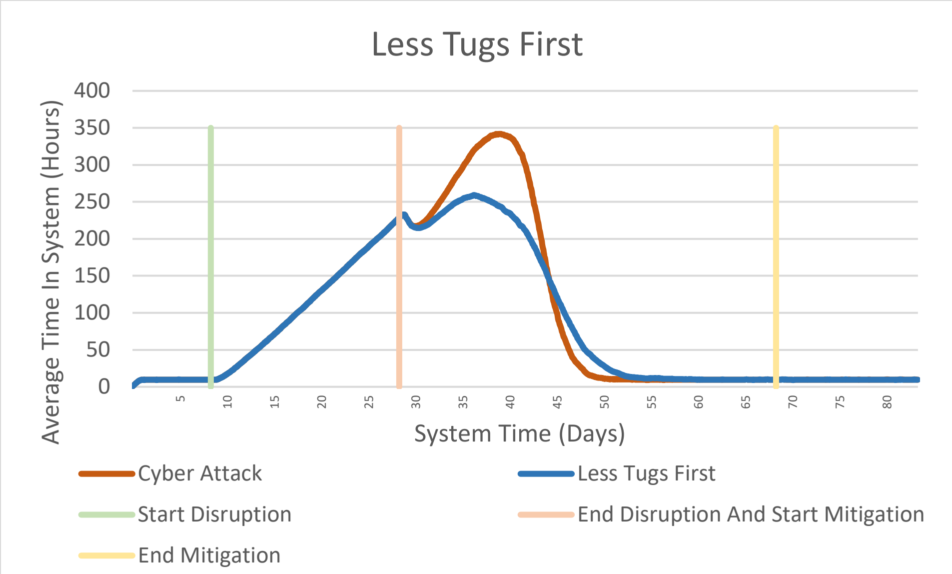


Figure C.13: Result of less tugs first with an cyber-attack

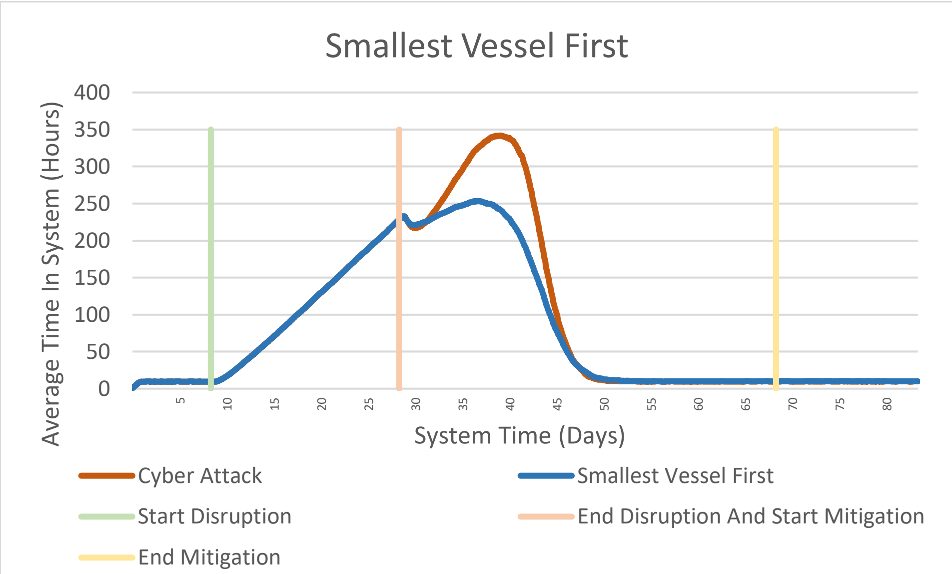


Figure C.14: Result of smallest vessel first with an cyber-attack

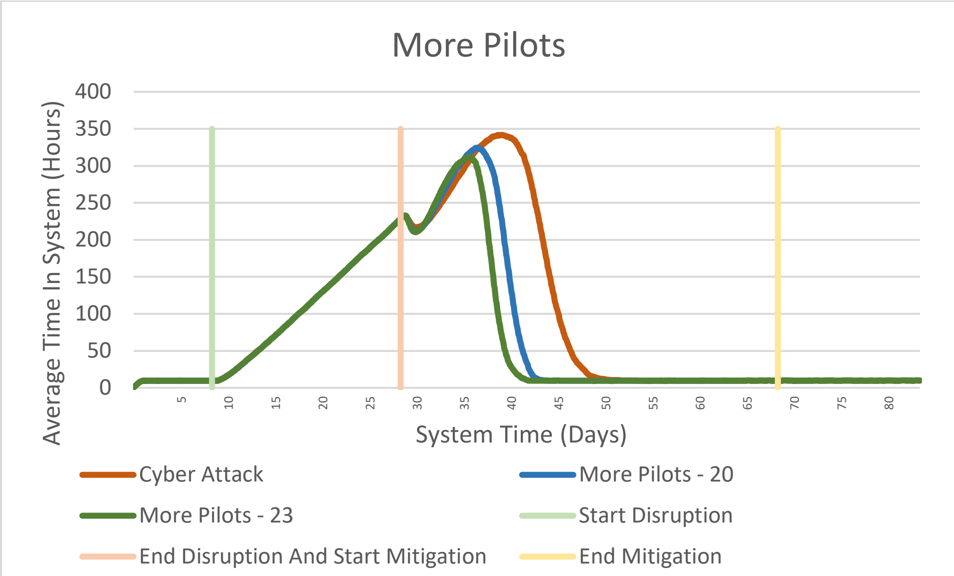


Figure C.15: Result of increasing pilots with an cyber-attack

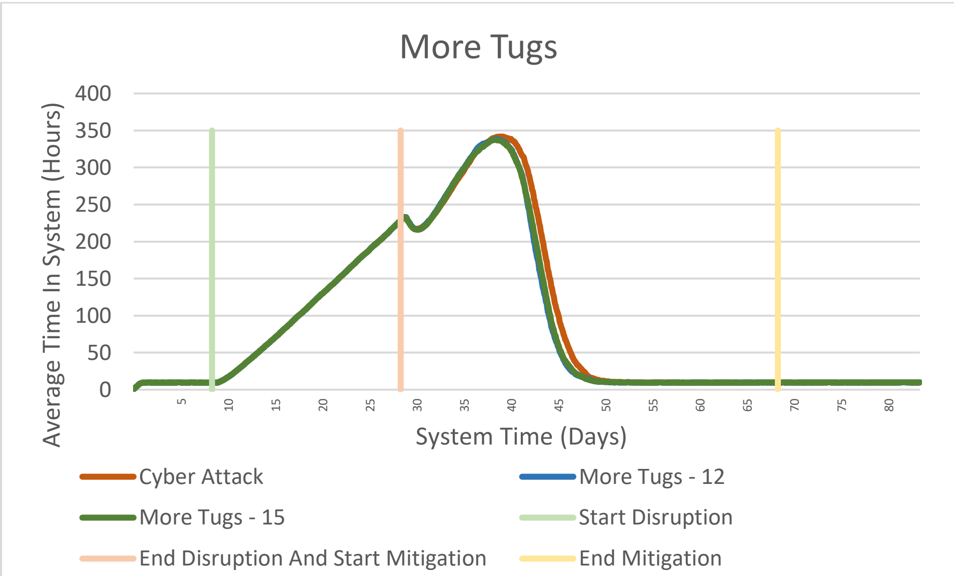


Figure C.16: Results of increasing tugs with an cyber-attack

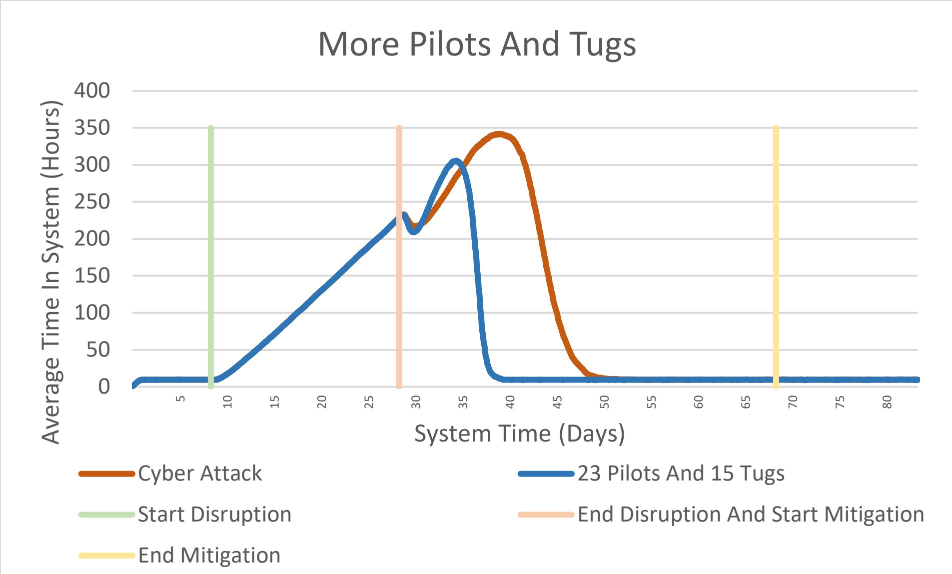


Figure C.17: Result of an simultaneous increase in pilots and tugs with an cyber-attack

C4. Pandemic outcomes

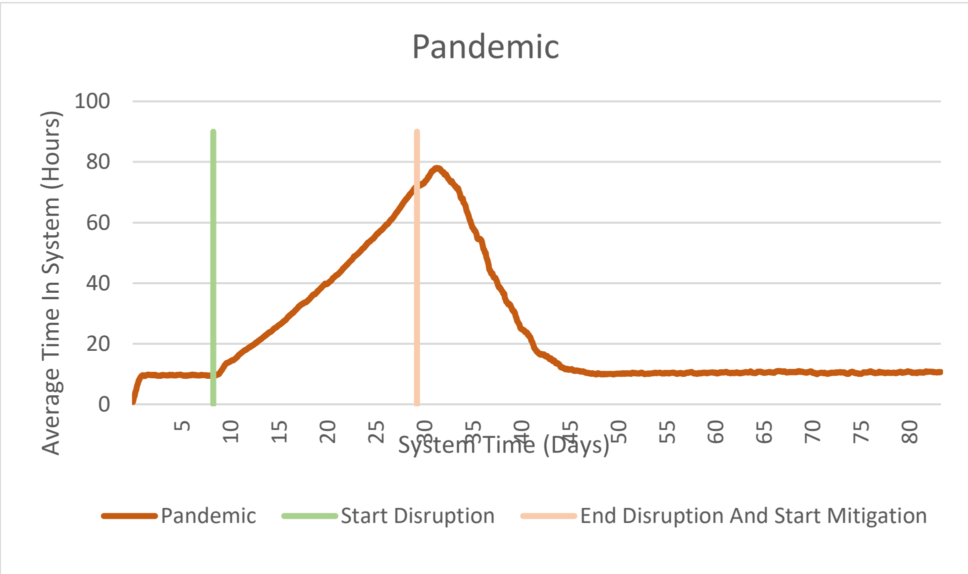


Figure C.18: Result of a pandemic on the base-case

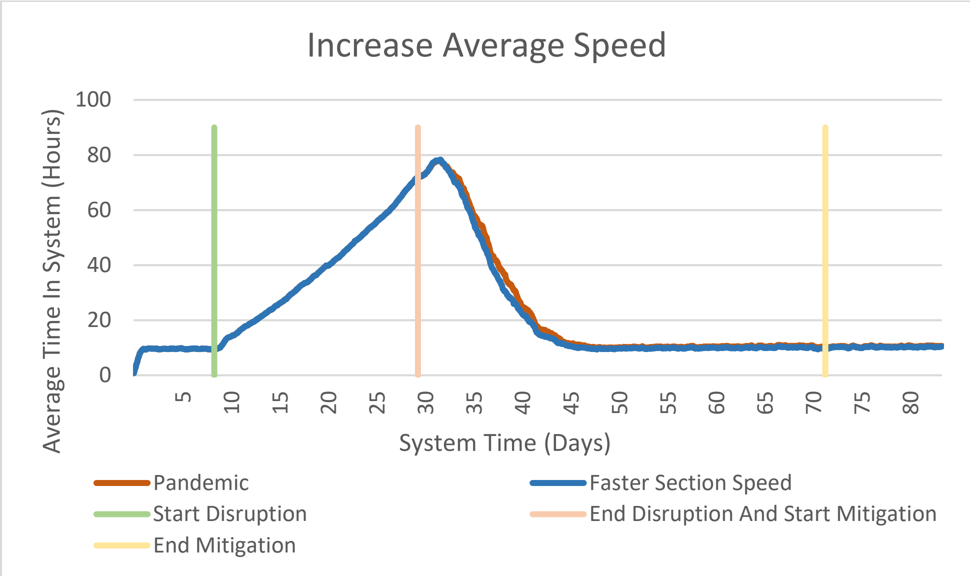


Figure C.19: Result of increasing the average speed with an pandemic

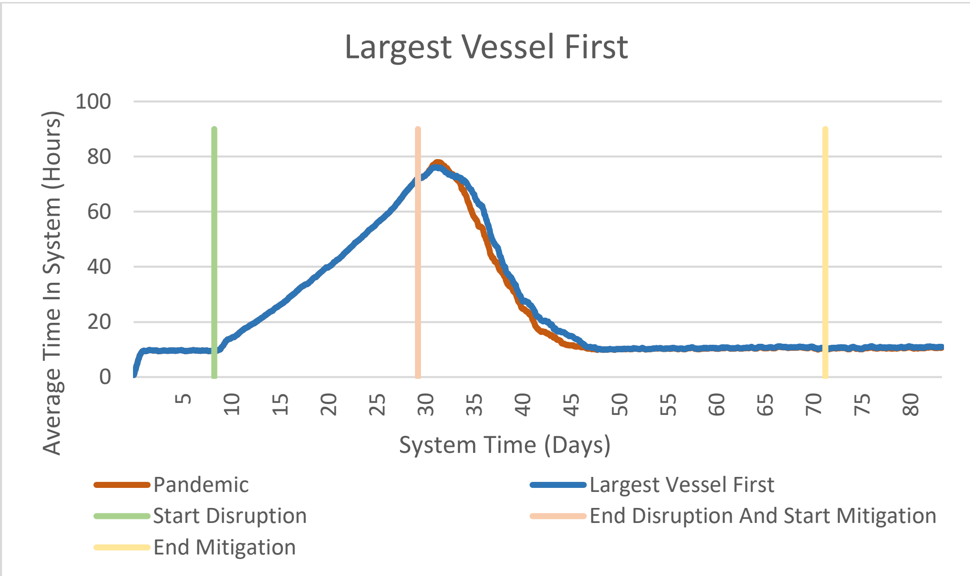


Figure C.20: Result of largest vessel first with an pandemic

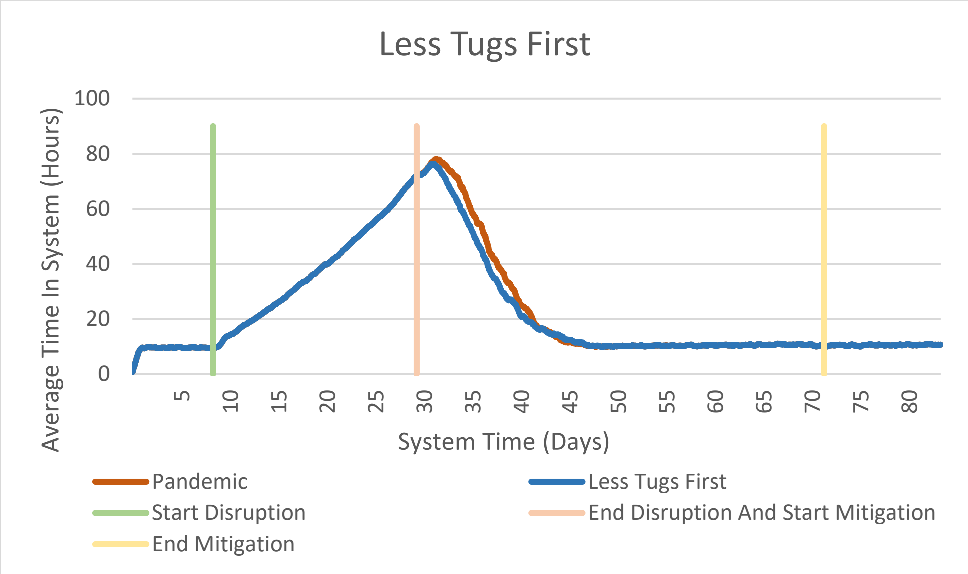


Figure C.21: Result of less tugs first with an pandemic

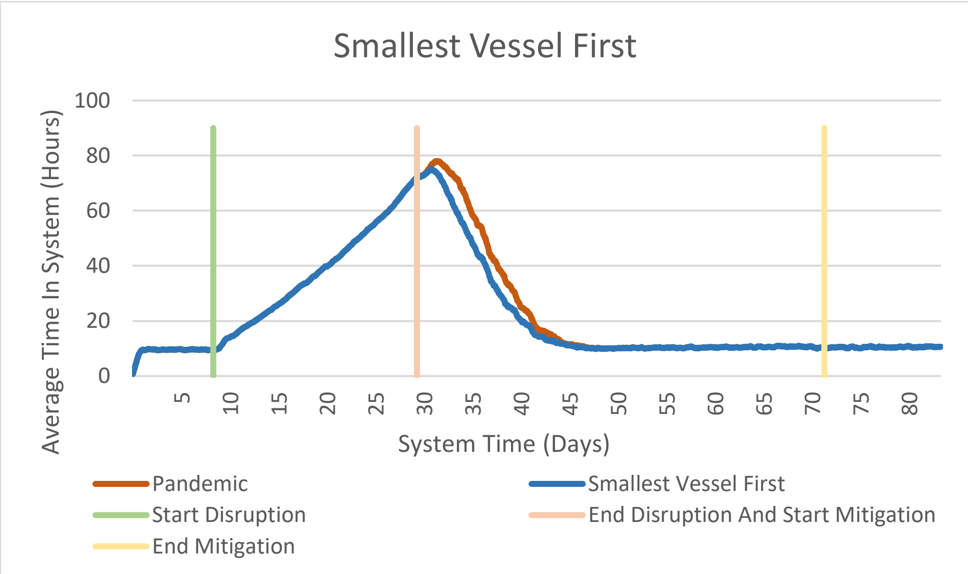


Figure C.22: Result of smallest vessel first with an pandemic

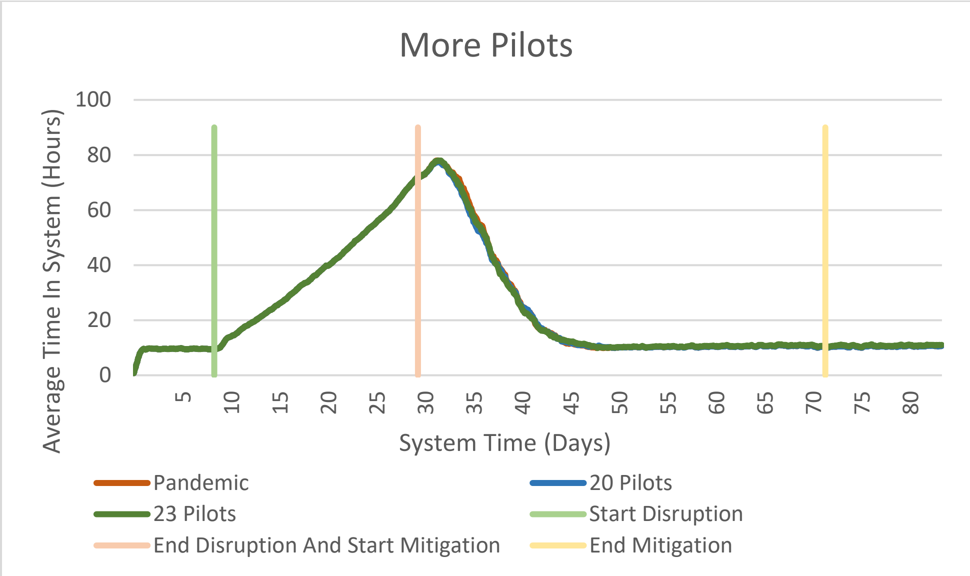


Figure C.23: Results of increasing pilots with an pandemic

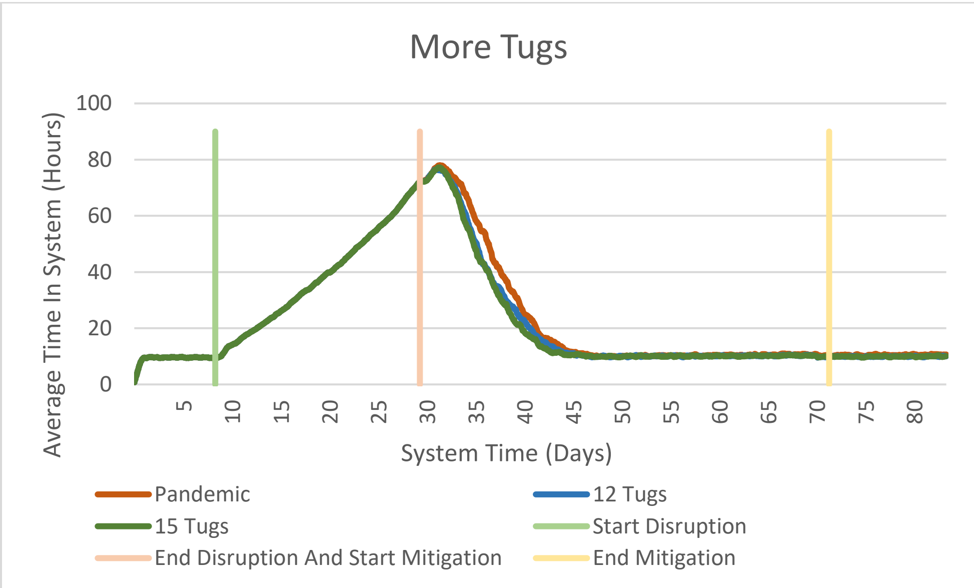


Figure C.24: Results of increasing tugs with a pandemic

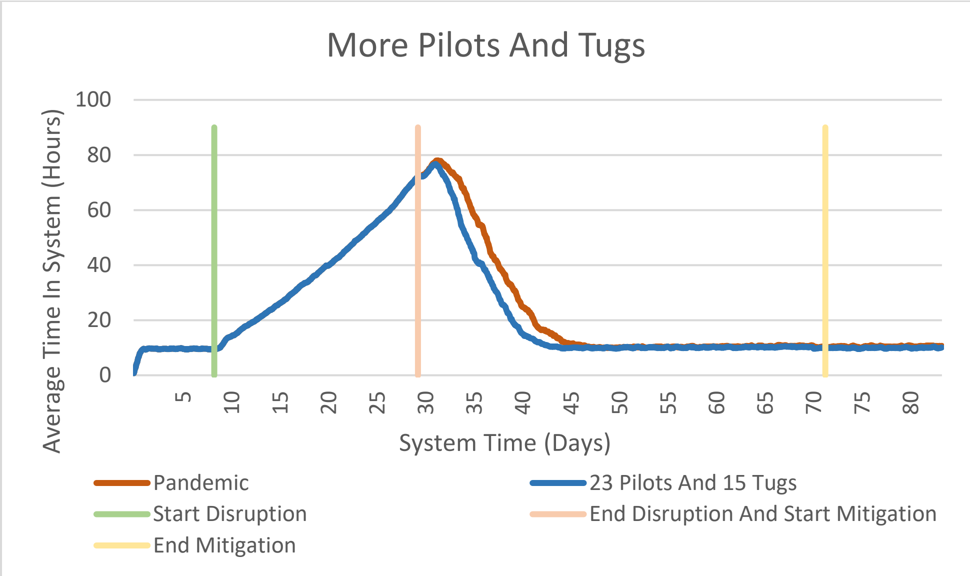


Figure C.25: Result of a simultaneous increase in pilots and tugs with a pandemic

C5. Suez Canal blockage outcomes

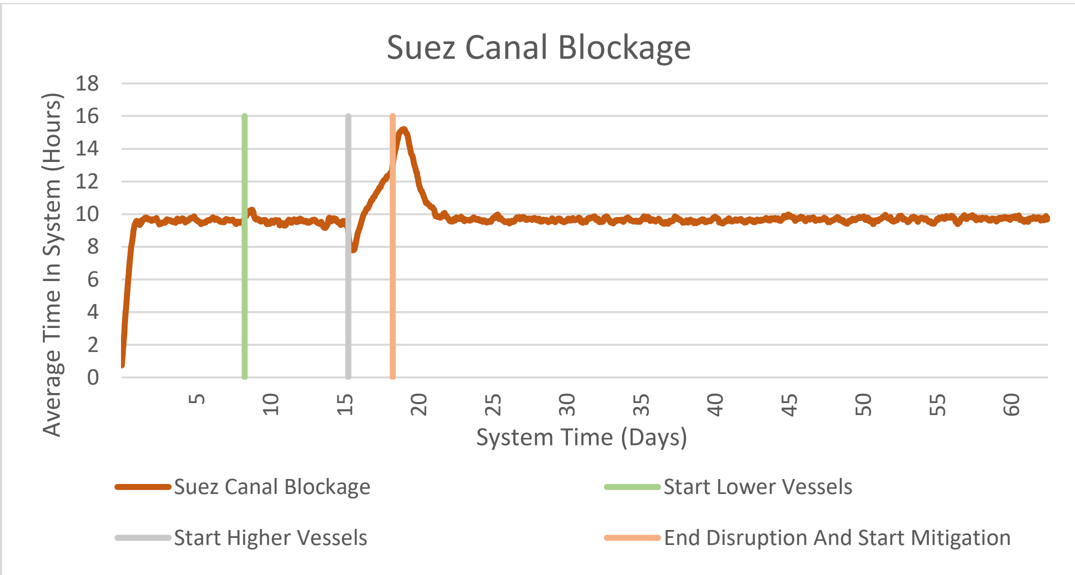


Figure C.26: Results of the Suez Canal blockage on the base-case

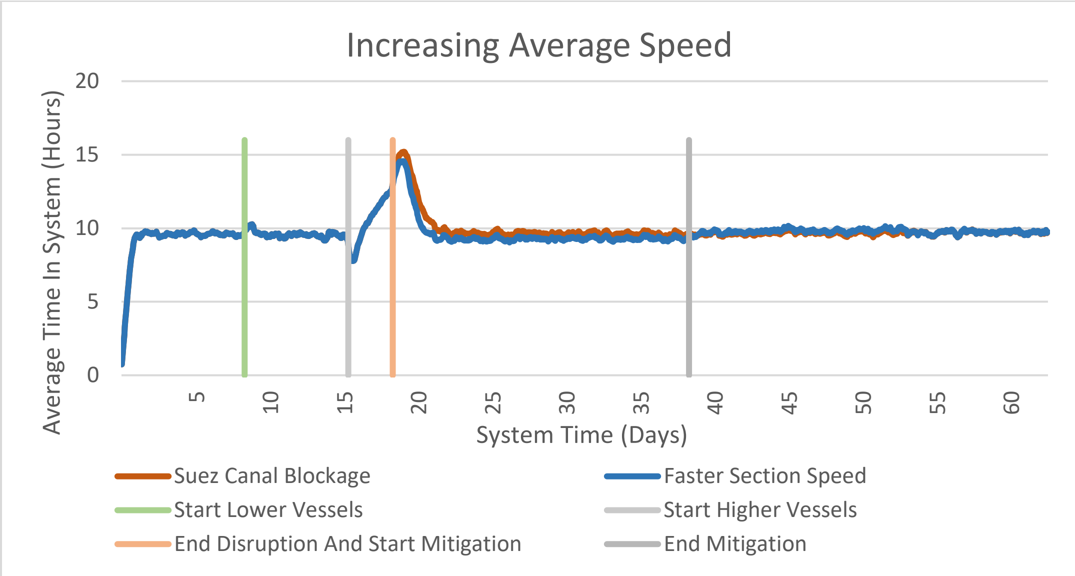


Figure C.27: Results of increasing the average speed with the Suez Canal blockage

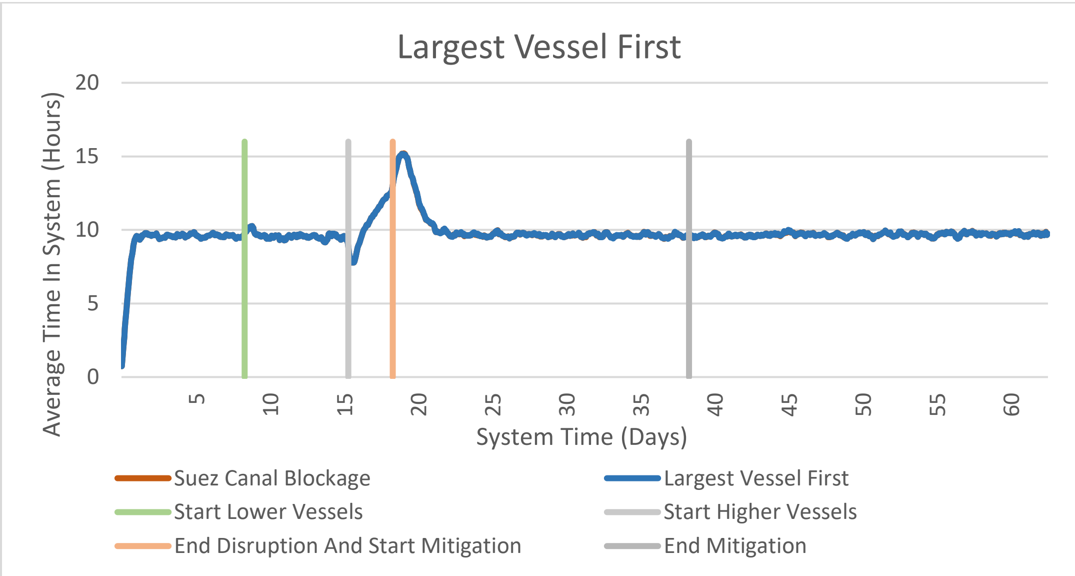


Figure C.28: Results of largest vessel first with the Suez Canal blockage

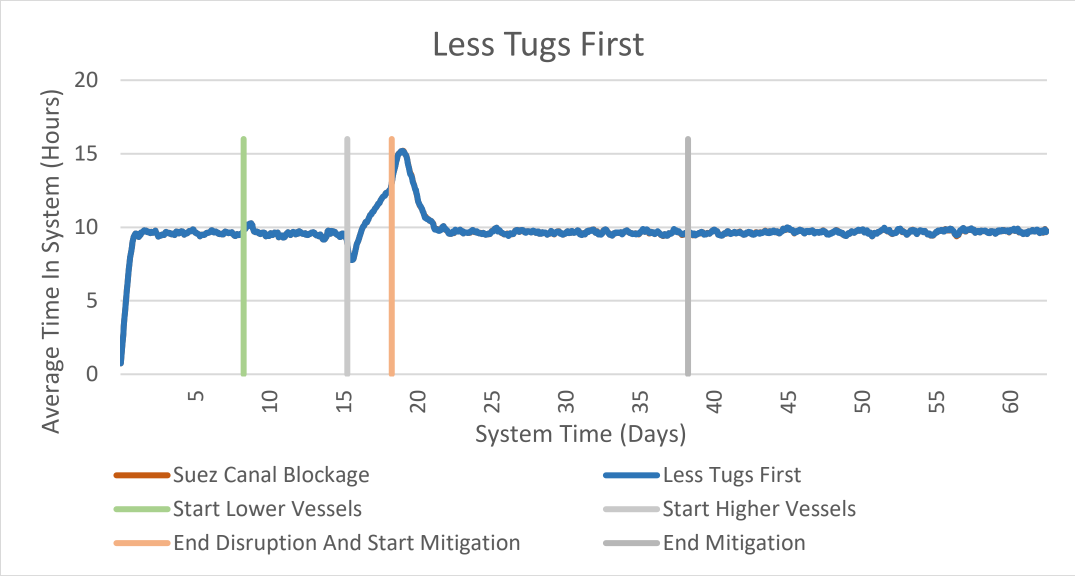


Figure C.29: Results of less tugs first with the Suez Canal blockage

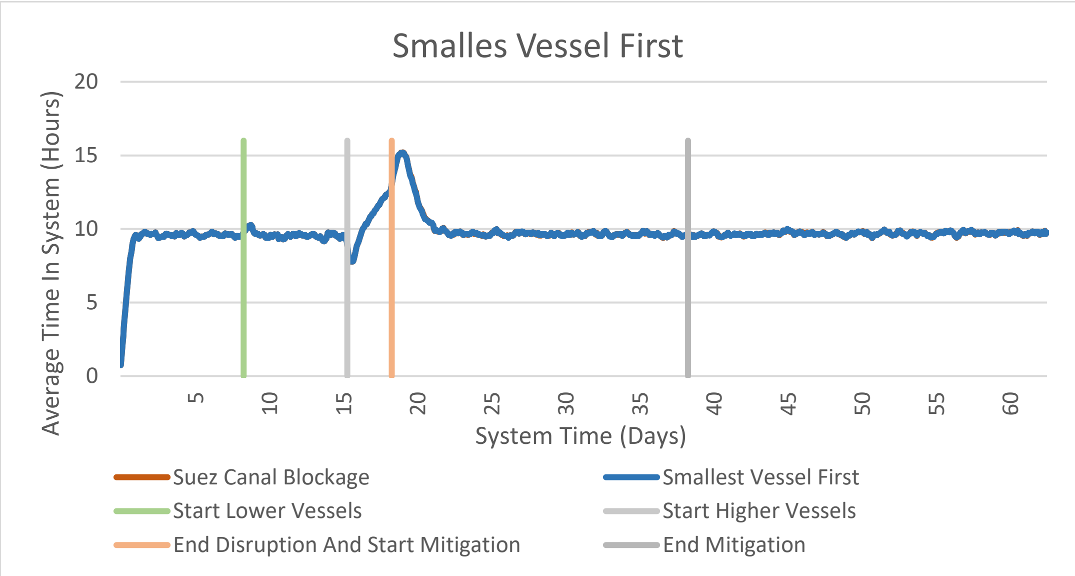


Figure C.30: Results of smallest vessel first with the Suez Canal blockage

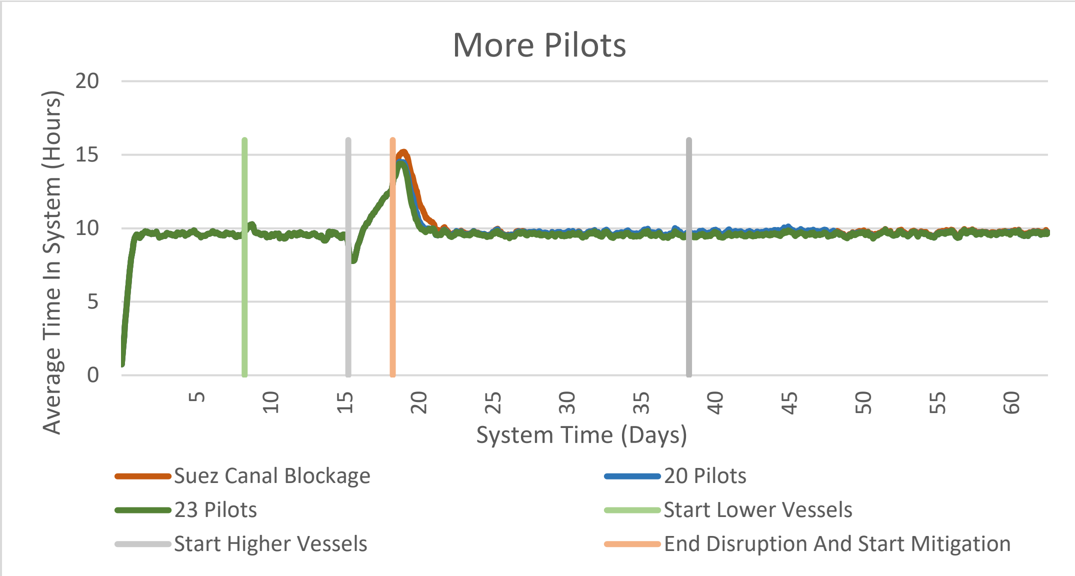


Figure C.31: Results of increasing pilots with the Suez Canal blockage

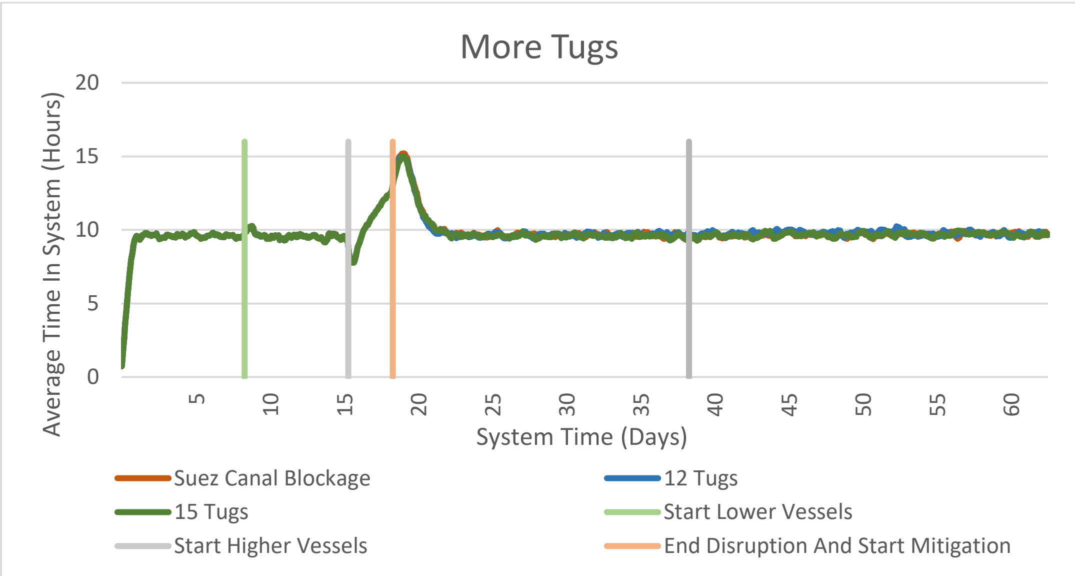


Figure C.32: Results of increasing tugs with the Suez Canal blockage

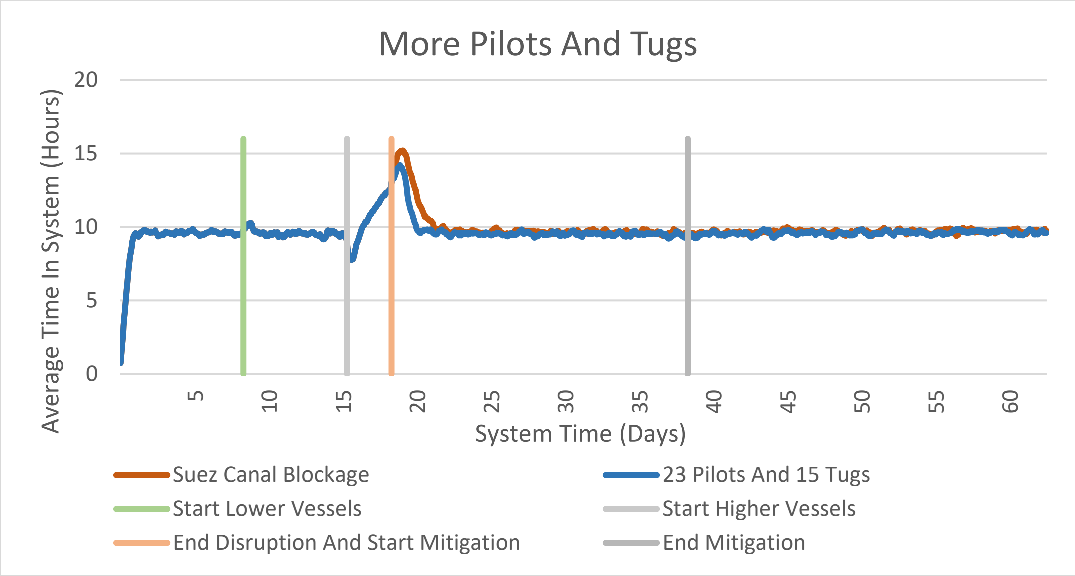


Figure C.33: Results of a simultaneous increase of tugs and pilots with the Suez Canal blockage

C6. Weather outcomes

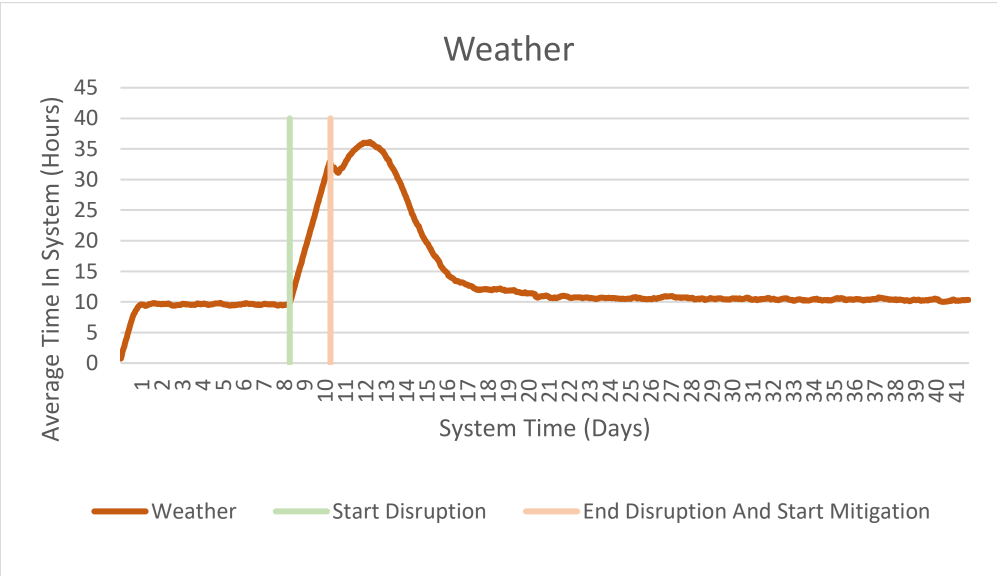


Figure C.34: Results of the weather scenario in the base-case

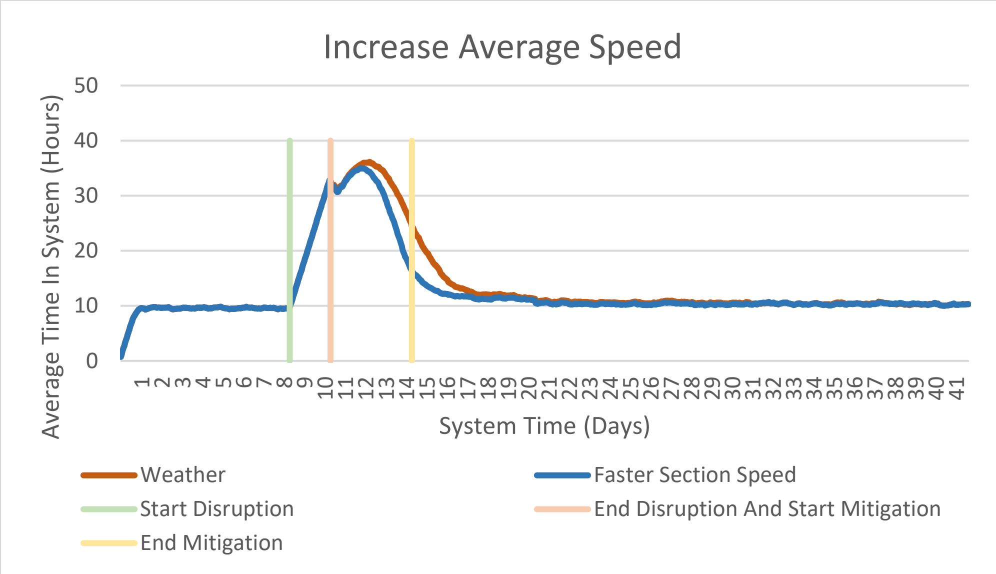


Figure C.35: Results of increasing the average speed with extreme weather

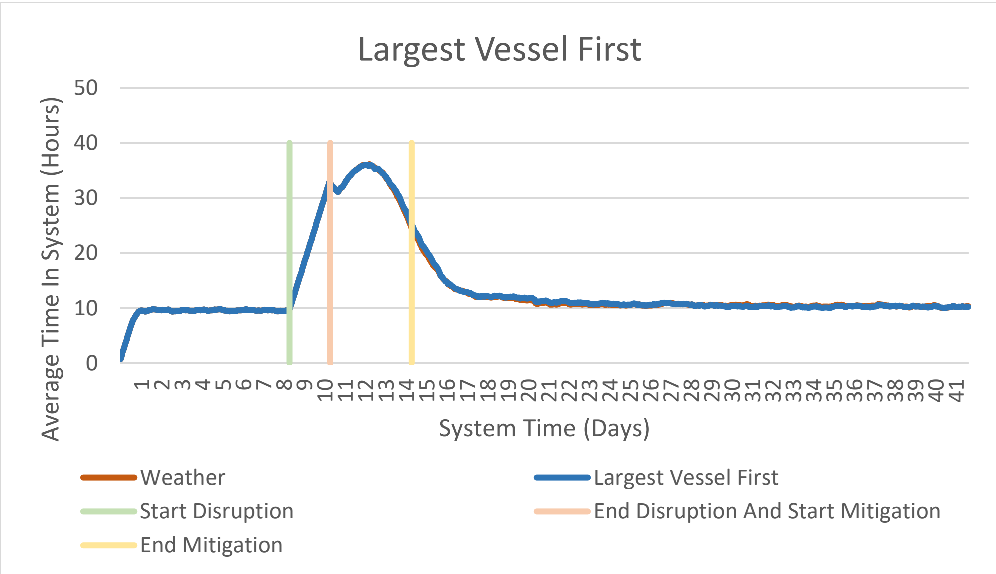


Figure C.36: Results of largest vessel first with extreme weather

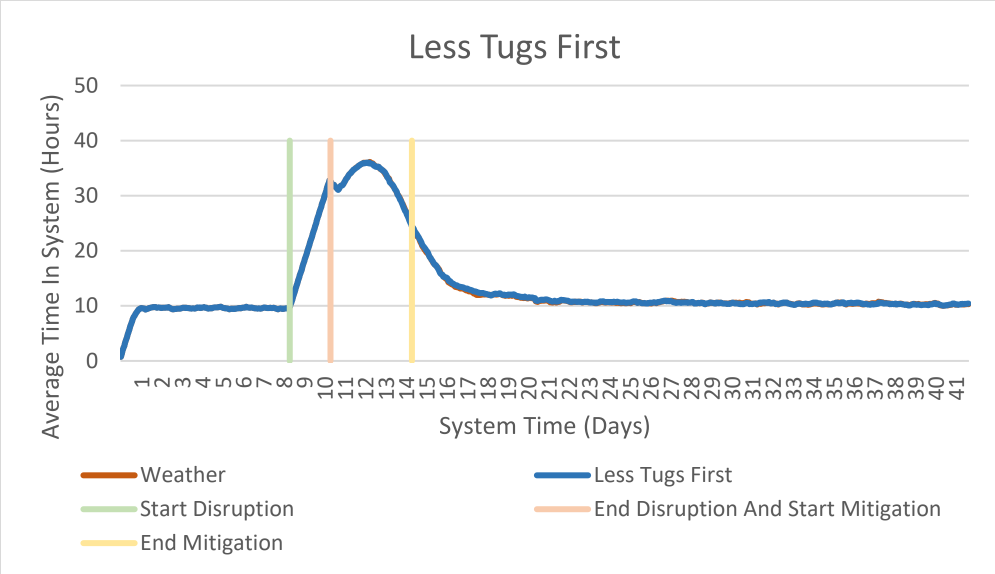


Figure C.37: Result of less tugs first with extreme weather

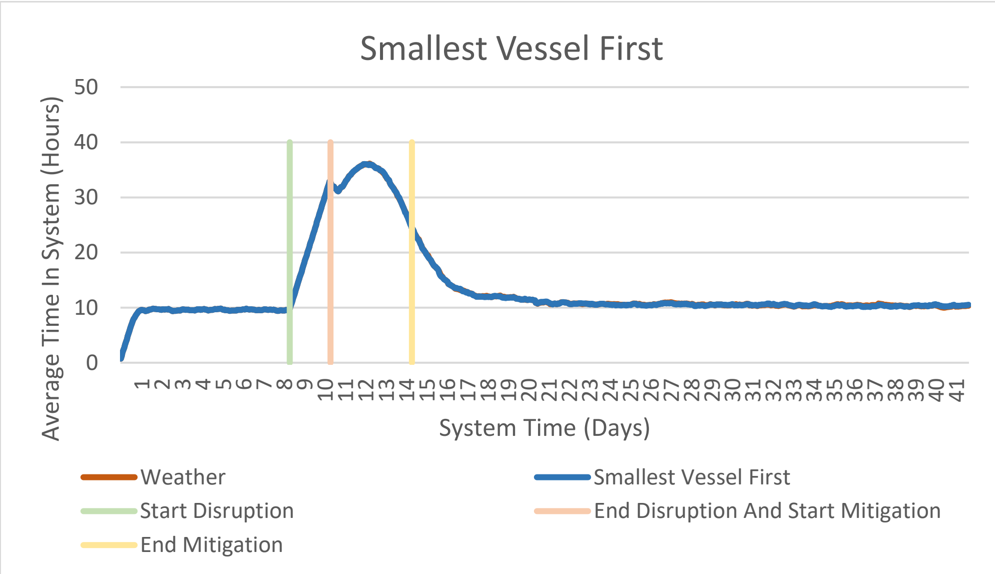


Figure C.38: Results of smallest vessel first with extreme weather

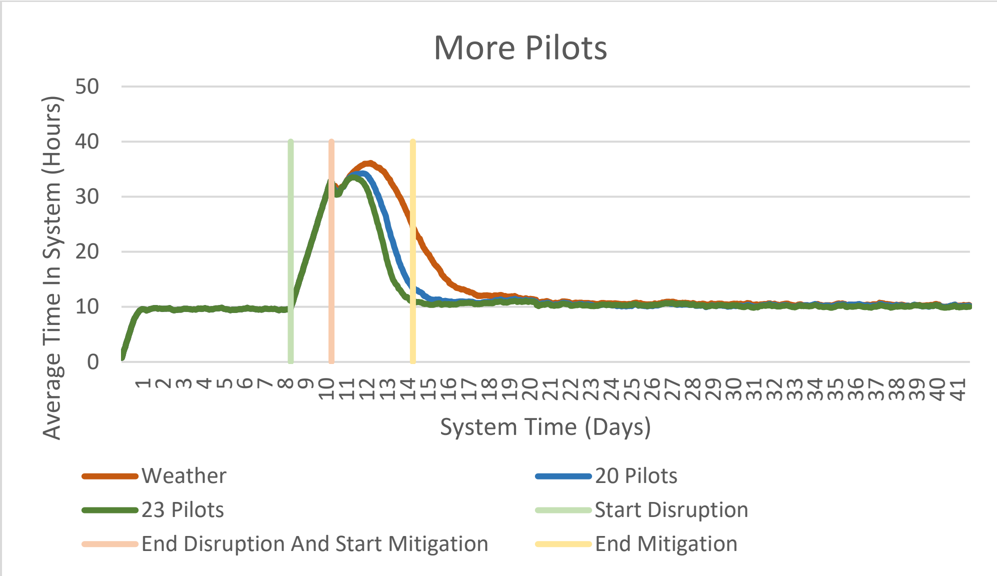


Figure C.39: Results of increasing pilot with extreme weather

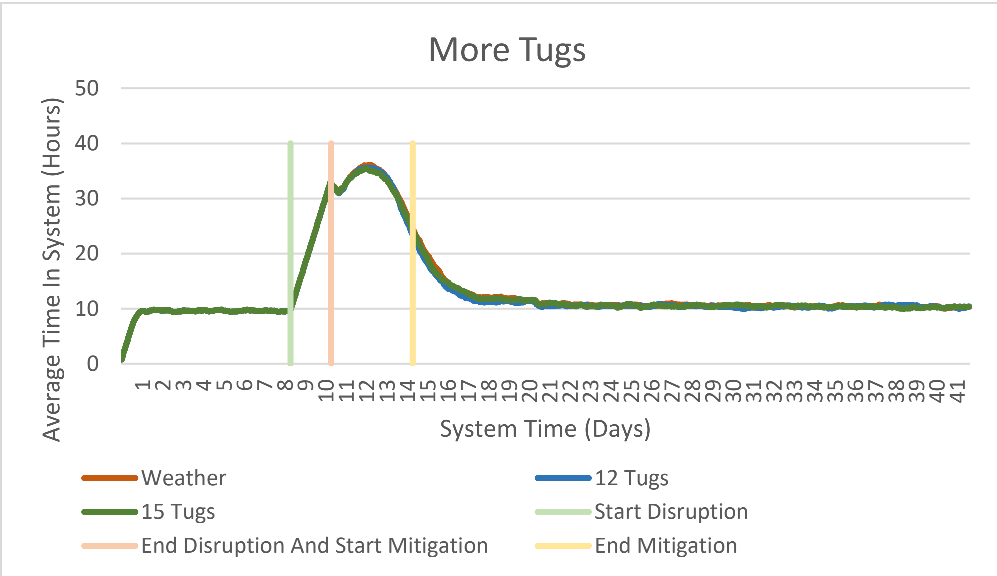


Figure C.40: Results of increasing tugs with extreme weather

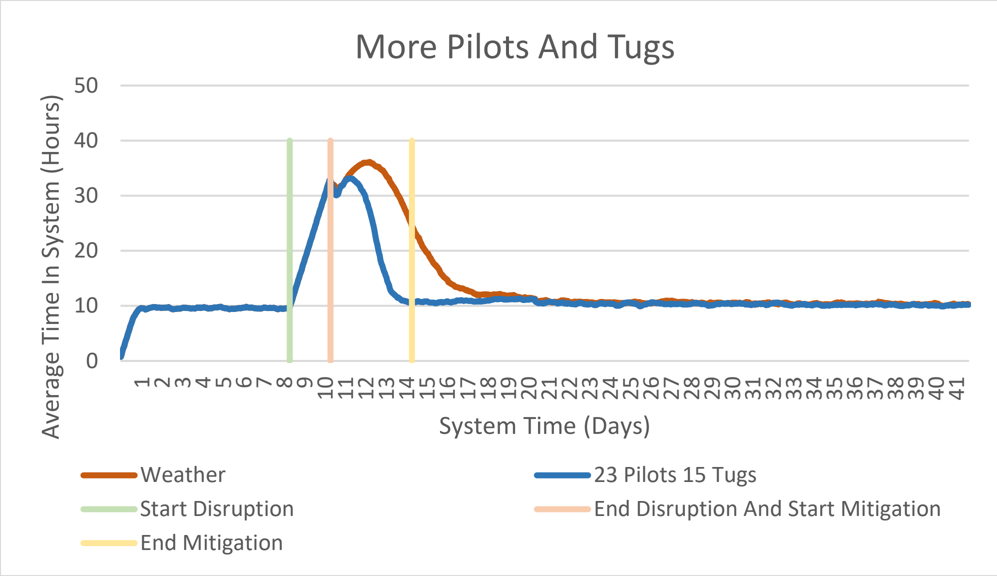


Figure C.41: Result of a simultaneous increase of pilots and tugs with extreme weather