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Optimization and Simulation of a Maritime Transportation System with Transshipments at Sea

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Purpose of Master's Thesis

The purpose of this Master's thesis is to develop a mathematical model and solution method(s) for a conceptual liner shipping network operating along the Norwegian coastline, referred to as the Short Sea Pioneer logistics system. An important aspect with the Short Sea Pioneer logistics system is synchronized transshipments between container ships at sea. A solution approach for the problem should examine and evaluate how obtained solutions may act in a real world situation.

Main contents: 1. Description of the problem 2. Presentation of mathematical model 3. Implementation of mathematical model 4. Computational study of the model with realistic data

Preface

This Master's thesis is the concluding part of our Master of Science at the Norwegian University of Science and Technology (NTNU). Our degree specialization is Managerial Economics and Operations Research at the Department of Industrial Economics and Technology Management.

This Master's thesis is a continuation of the work with our specialization project in the fall semester of 2016 ([Holm and Medbøen, 2016](#)) and aims to find a fleet deployment plan and a liner shipping network configuration for the Short Sea Pioneer logistics system. New to this Master's thesis is the inclusion of weather uncertainty and several refinements such as an improved mathematical formulation of the optimization problem.

We would like to thank our supervisors Kjetil Fagerholt and Peter Schütz for excellent guidance and feedback throughout the project.

The Master's thesis is written as a part of a larger project, namely the Short Sea Pioneer. Several industry partners are involved and we would like to give a special thanks to the shipping company NCL (NorthSea Container Line) for being genuinely interested in our work and giving us valuable input and a greater understanding of the Short Sea Pioneer logistics system. Further, we would like to thank Kay Fjørtoft from SINTEF Ocean, in addition to Sverre Anders Alterskjær as he helped us understand how to apply basic hydrodynamic principles in our simulation model.

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Abstract

This Master's thesis presents an operations research study of the Short Sea Pioneer logistics system which is a conceptual maritime logistics system between continental Europe and the Norwegian coastline. The aim is to make short sea shipping more cost efficient and attractive by having transshipments at sea between mother and daughter ships.

Few guidelines regarding system designed are determined, and this Master's thesis presents a modeling framework to establish a deeper understanding of how the concept might be realized. The framework combines an optimization and a simulation model in order to find a fleet deployment plan and a liner shipping network configuration taking weather uncertainty into account.

The optimization model includes a route generation procedure and a master problem. A path flow formulation is chosen and candidate routes are generated using an a-priori dynamic programming label-setting algorithm. A solution from the optimization model is a route composition consisting of one main route and one or more daughter routes. The objective is to minimize operational costs while ensuring that all ports are visited weekly.

The simulation model is implemented to evaluate the performance of a solution under realistic weather conditions. If a solution cannot maintain a weekly port visit frequency, a penalty cost is assigned. An iterative feedback process between the optimization and the simulation model is implemented and referred to as the solution triggered feedback approach. The output from the simulation model is sent back to the master problem enabling it to find better solutions. The result is a solution that performs well taking both operational cost and behavior under realistic weather conditions into consideration.

Several performance-improving strategies are implemented to find solutions that perform well under realistic weather conditions. In addition, a simplified simulation approach without any iterations between the master problem and the simulation model is used as a benchmark to discuss the value of the solution triggered feedback approach.

The results show that solutions found using the optimization model alone perform poorly when simulated. However, when using performance-improving strategies, the obtained solutions perform significantly better. In addition, the solution triggered feedback approach seems to find better solutions than the simplistic approach.

The findings in this Master's thesis can be used as decision support in the development of the Short Sea Pioneer logistics system. Since the system is in a conceptual phase, different input parameters can be tested to see how the results are affected. By doing this, a decision maker can use their experience and expert judgment to evaluate the Short Sea Pioneer logistics system in a broader context.

Sammendrag

Denne masteroppgaven presenterer en studie av Short Sea Pioneer logistikksystemet ved bruk av operasjonsanalyse. Short Sea Pioneer logistikksystemet er et konseptbasert maritimt logistikksystem mellom det kontinentale Europa og norskekysten. Målet er å gjøre nærskipfarten mer attraktiv ved å ha omlastninger til sjøs mellom mor- og datterskip.

Få retningslinjer for systemdesign er bestemt, og denne masteroppgaven presenterer et optimering-simulerings rammeverk for å etablere en dypere forståelse av hvordan konseptet kan realiseres. Rammeverket består av en optimeringsmodell og en simuleringsmodell, og har som mål å finne en flåtekomposisjon og rutesammensetning som også tar hensyn usikkerhet i været.

Optimeringsmodellen inkluderer en rutegenereringsprosedyre og et masterproblem. En rutebasert formulering brukes og kandidatruiter genereres med en a priori dynamisk labellingsalgoritme. En løsning fra optimeringsmodellen er en rutesammensetning som består av en hovedrute og en eller flere datterruiter. Målet er å minimere operasjonelle kostnader samtidig som alle havnene blir besøkt hver uke.

Simuleringsmodellen er implementert for å evaluere ytelsen til en løsning under realistiske værforhold. Hvis en løsning ikke kan opprettholde en ukentlig besøksfrekvens i havnene legges det til en straffekostnad. En iterativ tilbakemeldingsprosess mellom simuleringsmodellen og optimeringsmodellen som tar i bruk løsningsbasert respons er implementert for å undersøke større deler av løsningsrommet. Det endelige resultatet fra optimering-simulerings rammeverket er en løsning som presterer bra tatt både operasjonelle kostnader og oppførsel under realistiske værforhold i betraktning.

Flere ytelsesforbedrende strategier er implementert for å finne løsninger som presterer bedre under realistiske værforhold. I tillegg er en forenklet løsningsmetode uten noen iterasjoner mellom masterproblemet og simuleringsmodellen brukt som sammenligningsgrunnlag for å diskutere verdien av løsningsmetoden med løsningsbasert respons.

Resultatene viser at løsninger som finnes ved hjelp av den matematiske modellen alene, presterer dårlig under realistiske værforhold. Løsningene som er funnet ved hjelp av prestasjonsforbedrende strategier presterer betydelig bedre. I tillegg ser løsningsmetoden med løsningsbasert respons ut til å finne bedre løsninger enn den forenklete metoden.

Funnene i denne masteroppgaven kan brukes som beslutningsstøtte i utviklingsprosessen av Short Sea Pioneer logistikksystemet. Siden systemet er i en konseptfase og få detaljer er klarlagte, kan hva-skjer-hvis analyser gi innsikt i hvordan logistikksystemet kan utformes. På denne måten kan en beslutningstaker bruke sin erfaring og ekspertise til å evaluere Short Sea Pioneer logistikksystemet med ulike innfallsvinkler.

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Chapter 1

Introduction

This Master's thesis studies how operations research can be applied to a new, conceptual maritime transportation system referred to as the Short Sea Pioneer (SSP) logistics system. The system consists of mother ships serving a main route between the European continent and Norway, and daughter ships operating feeder routes along the Norwegian coastline. Contrary to a conventional shipping system, mother and daughter ships can perform transshipments at sea while being coupled together. The overall goal with the Short Sea Pioneer logistics system is to make short sea container shipping more attractive and cost efficient.

The concept is developed in a collaborative project, called the Short Sea Pioneer. It includes many industry partners and is funded by the Norwegian Research Council. The initiator is NCE Maritime CleanTech - an organization engaged in creating innovative solutions for the maritime sector in Norway. Two important contributing partners, both in the Short Sea Pioneer and this Master's thesis, are the shipping company NCL (NorthSea Container Line) and SINTEF Ocean.

1.1 Trends in the Norwegian Short Sea Sector

By 2030, the demand for cargo transportation in Norway is expected to grow by 40% tonne-kilometre, whereby the highest growth is expected for road-based transportation ([Meld.St. 26 \(2012-2013\)](#)). There is, however, a strong political focus on moving more goods from road to sea and railroad. The Norwegian government aims at moving 30% of all cargoes transported by road over distances longer than 300 kilometers to sea and railroad within 2029 ([Meld.St. 33 \(2016-2017\)](#)). With today's volumes, this accounts for about 7 mill. tonnes of goods yearly, and 11 mill. tonnes based on expected volumes in 2030.

The rationale behind this shift relates to environmental and socioeconomic considerations. Currently, shipping is considered the most environmentally friendly transportation alternative ([Grønt Kystfartsprogram, 2016](#)) in terms of greenhouse gas emissions. Further, sea transportation reduces road congestion and attrition. Additionally, the number of heavy goods vehicle accidents is expected to decrease with fewer trucks on the road ([Meld.St. 33 \(2016-2017\)](#)).

The Norwegian short sea sector can be defined to include shipping between Norwegian ports, and shipping between Norwegian and European ports. Currently, the Norwegian short sea sector is heavily exposed to competition and operates with low margins ([Sjøtransportalliansen, 2015](#)). An important challenge is high costs related to port visits, and according to NCL these costs constitute for about 30% of their turnover

(Stensvold, 2015). Another challenge is the average age of the fleet which is about 30 years (Sjøtransportalliansen, 2015). The fleet must be renewed in order to reduce bunker costs, meet future demands and stricter emission standards. Further, road based door-to-door transportation is often less expensive than alternative shipping solutions (Haram, Hovi and Caspersen, 2015) and thus shipping companies need to reduce their costs and offer a lower price to become more attractive.

Providing a reliable and punctual transportation service increases the attractiveness of sea transportation. Time-related criteria, such as a reliable port visit frequency, is next after price the most determining factor for whether or not transportation by sea is chosen (Kystverket, 2016). Deviations in arrival times increase costs for cargo owners as they must operate with larger time buffers. Further, these deviations lead to extra port costs for shipping companies and can cause trouble for connected ship routes. Additionally, deviations in port arrivals decrease port effectiveness and cause longer waiting-times.

The goal of providing better punctuality in container ship services has recently been manifested in the Norwegian Transportation Plan (Meld.St. 33 (2016-2017)). Weather uncertainty is an important source leading to delays and is the reason why the Norwegian government has decided to build the worlds' first ship tunnel as a shelter for harsh weather in the coastal area around Stadt.

Supporting new and innovative ideas can trigger a change from road to water-based transportation. In this regard, the Short Sea Pioneer logistics system forms a novel solution for the future of Norwegian container shipping. According to early analysis, NCL can save as much as 60 million NOK, corresponding to about 15% of their total turnover with the Short Sea Pioneer logistics system (Stensvold, 2015).

1.2 Benefits with the Short Sea Pioneer Concept

The fact that mother ships sail on a main route and daughter ships sail on feeder routes delivering and picking up cargoes both from ports and mother ships, utilizes advantages of hub & feeder networks. Alumur and Kara (2008) point out that such networks concentrate flows to potentially take advantage of economies of scale.

In a conventional maritime hub & feeder network, transshipments are done in a port where cargoes delivered by a ship are stored until another ship picks up the cargoes for further transportation. This cargo storage induces inventory costs which could be avoided if transshipments are done at sea instead. Further, costs related to port fees can be reduced as there is no longer a need for two ships visiting the same port in order to transship cargoes.

Along the Norwegian coastline, and especially inside the fjords, many ports are too small to be visited by large container ships. This results in road transportation of cargoes from a location near small ports to bigger ports. In some cases, the cargo is transported by trucks all the way to its destination. The CEO in NCL explains that expanding small ports to be suitable for large ships takes several years, is costly and in some places, it is not even possible at all (Stensvold, 2015). The Short Sea Pioneer logistics system is, therefore, a more flexible and accessible transportation system for cargo owners located near small ports.

1.3 Contribution and Purpose

The Short Sea Pioneer logistic system is a complex concept involving several industry partners and deciding whether the concept is realizable or not is an overall decision beyond the scope of this Master's thesis. The purpose of this Master's thesis is to gain a deeper understanding of the Short Sea Pioneer logistics system and its underlying implications.

Operations research is used to study the system from a logistical and economical point of view. In a framework combining optimization and simulation, potential route compositions are selected and simulated in order to evaluate how they are affected by weather uncertainty. A feedback loop between the optimization model and the simulation model makes it possible to search for solutions with potentially enhanced performance. To the best of the authors' knowledge, this solution approach has not been applied in a similar setting before and from a decision maker's perspective, this can provide valuable insights into how the Short Sea Pioneer logistics system might be realized.

1.4 Structure of Master's Thesis

This Master's thesis is organized as follows: Chapter 2 provides a more detailed explanation of the Short Sea Pioneer logistics system. In Chapter 3, a problem description that forms the baseline for the following chapters is given. Chapter 4 reviews relevant literature, focusing mainly on liner shipping network design problems and disruption management. An overview of the optimization-simulation framework and needed assumptions are given in Chapter 5. The mathematical formulation of the master problem and the route generation procedure are described in Chapters 6 and 7 respectively. The simulation model is described in Chapter 8. Further, Chapter 9 describes input data, while the results are presented in Chapter 10. Lastly, the conclusion and suggestions for future research are given in Chapter 11 and 12, respectively.

Chapter 2

Background

This chapter describes the Short Sea Pioneer (SSP) logistics system more in detail. Section 2.1 gives a brief introduction of NCL (NorthSea Container Line). Section 2.2 provides operational details about the outline of the SSP logistics system.

2.1 NorthSea Container Line

An important collaborative partner in this Master's thesis is the shipping company NCL (NorthSea Container Line). They are located in Haugesund, Norway, and have been in the short sea shipping industry since 1998. Currently, NCL operates five ships and their area of shipping covers the European cities Hamburg, Bremerhaven and Rotterdam in south, to the Norwegian city Stokmarknes in North. NCL services deep-sea shipping lines with feeder routes to and from Norway, visits industry ports and provides customers with a tailor-made door-to-door service.

2.2 A Closer Look at the SSP Logistics System

In this section a conceptual outline of the SSP logistics system is exemplified, and an overview of the current development plan is provided.

2.2.1 Conceptual Outline

In the SSP logistics system, mother and daughter ships operate a shipping network together along the Norwegian coastline and the continental Europe. Mother ships sail on a main route visiting larger ports. Daughter ships operate along feeder routes serving ports along the Norwegian coastline. The daughter ships can visit small ports not suitable for a large mother ship. The unique feature with the system is that a daughter ship can meet a mother ship at sea to load and unload cargoes. In other words, transshipments can be performed at sea instead of in a port. Because of this feature, there is a need for synchronizations between mother and daughter ships to make sure they are at the same location at the same time.

A simplified example to illustrate a conceptual outline of the SSP logistics system is shown in Figure 2.1. As seen in the figure, daughter ships sail inside fjords to serve small ports. At sea, they connect with a mother ship sailing on a main route between the continental Europe and the Norwegian coastline. The continental Europe is represented by Maasvlakte port located in Rotterdam, Netherlands. Both daughter

and mother ships are allowed to visit larger Norwegian ports. In the outline presented in the figure, Bergen is such a large port which is visited by a mother ship.

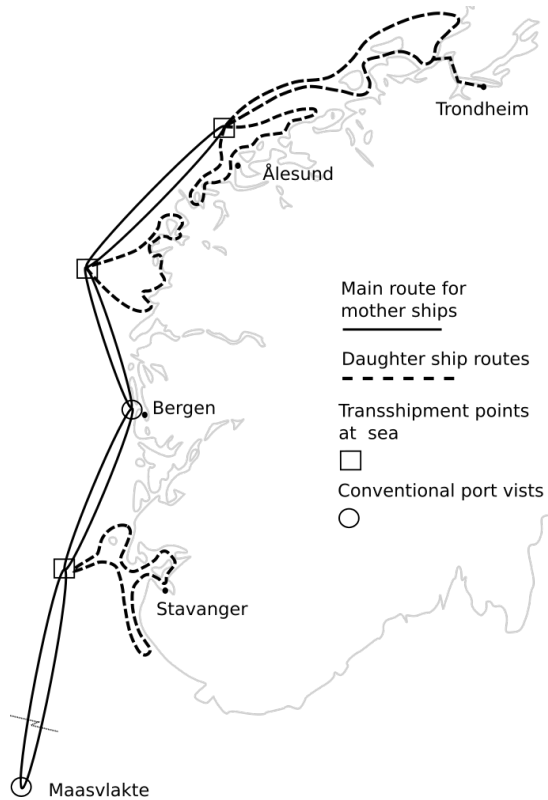


Figure 2.1: A conceptual route network that illustrates a potential outline of the SPP logistics system.

2.2.2 Transshipment at Sea

The locations at sea where transshipments take place can be compared to hub ports in a conventional shipping system. In Figure 2.1, these locations are placed a distance away from the shore. In reality, however, these locations will be located inshore where sea conditions are calm.

When performing a transshipment, a daughter ship connects its stern to either side of a mother ship. The cargoes are then moved between the ships. The coupling between the ships is illustrated in the design sketch shown in Figure 2.2. This way of doing transshipments obviously requires specially designed mother and daughter ships. As of this reason, all daughter ships must have approximately the same size in order to connect with the mother ship. By having daughter ships of varying lengths some capacity differences are possible, but these differences are considered minor.

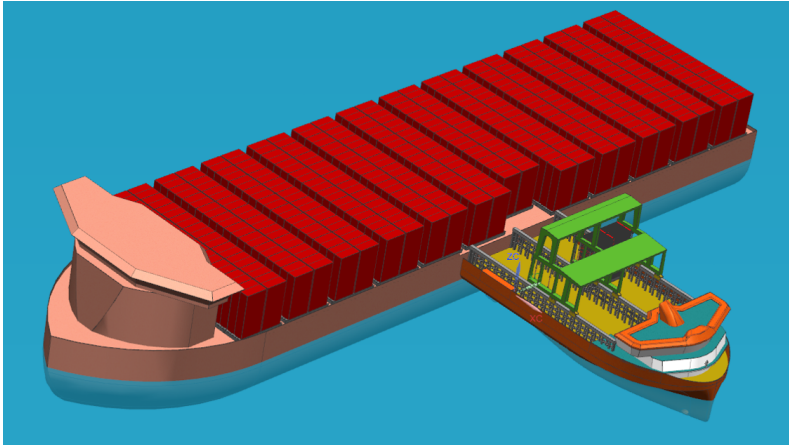


Figure 2.2: Transshipment at sea between a mother and daughter ship. Several containers are moved in a single lift to increase the cargo handling rate. Image used with permission from NCL.

An innovative cargo handling system is used to move cargoes between a mother and daughter ship. With this system, a batch of several containers can be transferred in one lift. This is possible by stacking several containers on top of each other. The containers are placed on a solid base frame that can be moved on a rail based system on the mother ship. The batch of containers are lifted with a special gantry crane. This crane is shown as the green structure on the daughter ship in Figure 2.2.

With NCL's current operations, one lift is typically required per container. By lifting several containers in one batch, NCL hopes to improve cargo handling rates drastically. An improved cargo handling rate will reduce the time needed to perform transshipments at sea. NCL hopes to achieve a cargo handling rate of 50 TEU/hour (50 twenty-foot containers per hour) with the new system. This is a drastic improvement compared to today's standard where a cargo handling rate of 20 TEU/hour is often considered high.

Please note that in an earlier design phase of the SSP logistics system, the coupling between mother and daughter ships was carried out a bit differently. With the old design, a daughter ship could sail into the stern of a mother ship to make them coupled together. However, this design is replaced by the new method provided in Figure 2.2.

2.2.3 Current Development Status

The SSP logistics system is still in an early phase, and hence the details of the concept are yet to be determined. Designing a maritime transportation system almost from scratch gives unique opportunities, but the high level of freedom gives challenges related to determining the best outline. Many design possibilities are not yet decided upon and only a few guidelines are proposed by NCL. A clear guideline is that all ports should be visited weekly. They also assume to use two mother ships sailing on one main route, each with a round trip of maximum two weeks.

With regards to cargo transport, the system will primarily be used for transportation

of cargoes to and from the Continental Europe. Thus, *local shipping*, which in this Master's thesis is defined as shipping between Norwegian ports, is not a primary focus for NCL.

Chapter 3

Problem Description

The earlier chapters have provided an overview of the SSP logistics system. Currently, the SSP logistics system is in a conceptual stage with few restrictions on how the system may be designed. It would quickly become too complex trying to consider many design possibilities at once. This chapter presents a problem description that captures a potential way of designing the SSP logistics system.

In Section 3.1, the problem description of the SSP logistics system is presented and referred to as the SSP problem. This problem description is based on the problem description in [Holm and Medbøen \(2016\)](#) and is verified by NCL as suitable for providing satisfying decision support in a conceptual stage. In Section 3.2, weather uncertainty is included to study how it can affect operational performance.

3.1 The SSP Problem

A maritime transportation system, such as the SSP logistics system, is to be configured as a hub and feeder network with transshipments at sea between mother and daughter ships. The system is to be operated between the Norwegian coastline and the European continent.

A fleet size and mix best fitted to serve the system must be selected. A set of routes serving a set of ports must be determined as well as a fleet deployment plan to allocate the ships in the fleet to the routes.

The objective is to minimize operating costs for the system which include a weekly time charter cost for each ship in the fleet, bunker (fuel) costs, port fees and cargo handling costs.

3.1.1 Ports, Routes and Service Frequency

A set of ports is available to visit and can be categorized according to four different port types. *Ocean hubs* correspond to suitable locations at sea where a transshipment between a mother and a daughter ship can occur. Each ocean hub can be artificially split into a south-going and a north-going ocean hub. An ocean hub that is visited by a mother ship sailing north is referred to as a north-going ocean hub. An ocean hub that is visited by a mother ship sailing south is referred to as a south-going ocean hub. *Coastal daughter ports* can only be visited by daughter ships. *Coastal main ports* can be visited by *either* a mother ship or a daughter ship. Coastal main ports are typically larger ports capable of docking a mother ship. The last port type is the *continental*

main port. This is the port on the European continent that only a mother ship can visit. There exists only one such port.

A port is associated with one and only one of the four port types. For example, a port cannot be both a coastal daughter port and a coastal main port. When a distinction between coastal daughter ports and coastal main ports are not necessary, they can be referred to as *coastal ports*.

All coastal ports and the continental main port must be visited once a week, but not all ocean hubs must necessarily be visited.

A route sailed by a daughter ship is referred to as a *daughter route*, and a route sailed by a mother ship is referred to as a *main route*. A daughter route can only be served by one daughter ship and it must be completed within one week (168 hours). Only one main route can be used, and it must be served with a weekly frequency by either one or two mother ships. If only one mother ship is deployed, it must be able to complete the main route within a week. If two mother ships are deployed, then each mother ship must be able to complete the main route within two weeks (336 hours). The maximum time to complete a route is further referred to *maximum allowed duration* and it applies for both main routes and daughter routes.

3.1.2 Demand and Cargo Capacity

There is a demand for cargoes to be transported to and from the continental main port. Shipping of cargoes between coastal ports, referred to as local shipping, is not considered. This is because the majority of cargoes transported by NCL are continental. In practice, however, after setting up the system, opportunities for local shipping could be seized if there is unused capacity on a daughter ship.

A ship cannot transport more cargoes than its given capacity. Cargoes at a port are always ready to be loaded or unloaded at any time. All cargoes must be transported from their origin to their destination.

All daughter ships in the fleet must have the same cargo capacity. The rationale behind this is due to technical limitations of the SSP logistics system. Since a mother ship must be designed capable of doing transshipments with daughter ships, the daughter ships must have approximately the same size. A few different types of daughter ships with different capacities are available to choose from. With regards to the capacity of a mother ship, it is assumed to always be big enough to transport all cargoes that need to be transported. Hence, it can be considered uncapacitated.

3.1.3 Transshipments

No more than one transshipment per cargo is allowed within the system, and a transshipment can only occur in an ocean hub. Each daughter ship can meet a mother ship once or twice every week for transshipments in ocean hubs.

If a daughter ship meets a mother ship twice, it must occur in the following way: a north-going mother ship can only deliver cargoes to a daughter ship, and a south-going mother ship can only pick up cargoes from a daughter ship. The meeting location must be in the same ocean hub.

The rationale behind this way of doing transshipments is that the transit time can be reduced for some of the cargoes. For instance, if a mother and daughter ship could only meet in a south-going ocean hub, cargoes coming from the continental main port would have to stay on a mother ship all the way to the northernmost point on the main route before unloading in the south-going ocean hub. Because of the possibly reduced transit time, NCL wants transshipments in both south-going and north-going ocean hubs.

When two ocean hubs are visited, it is important to consider the time a daughter ship has available between the visits. In this regard, it is convenient to refer to *loop 1* as the part of a daughter route that is between a north-going and a south-going ocean hub, and *loop 2* as the part of the daughter route that is between a south-going and a north-going ocean hub.

The time between two ocean hub visits for a daughter ship is determined by how far north or south the ocean hubs are located. If an ocean hub is the northernmost port on the main route, there is only meeting between a daughter and a mother ship in this ocean hub. Hence, there is no time to sail two loops and the daughter route is considered to be a loop 1. For ocean hub ports that are not the northernmost point on the main route, a daughter ship has time available on both loop 1 and 2. In these cases, a daughter ship has the opportunity to visit ports on loop 1 and 2. A mathematical approach of analyzing how much time a daughter ship has available between two ocean hub visits is conducted in Chapter 7.

3.1.4 Example

An example of a feasible solution to the SSP problem is given in Figure 3.1. In the figure, daughter ship "D1" meets the mother ship "M" twice a week while daughter ship "D2" meets the mother ship once a week. Only one mother ship is needed in this example. For simplicity, the mother ship in this example does not visit any coastal ports.

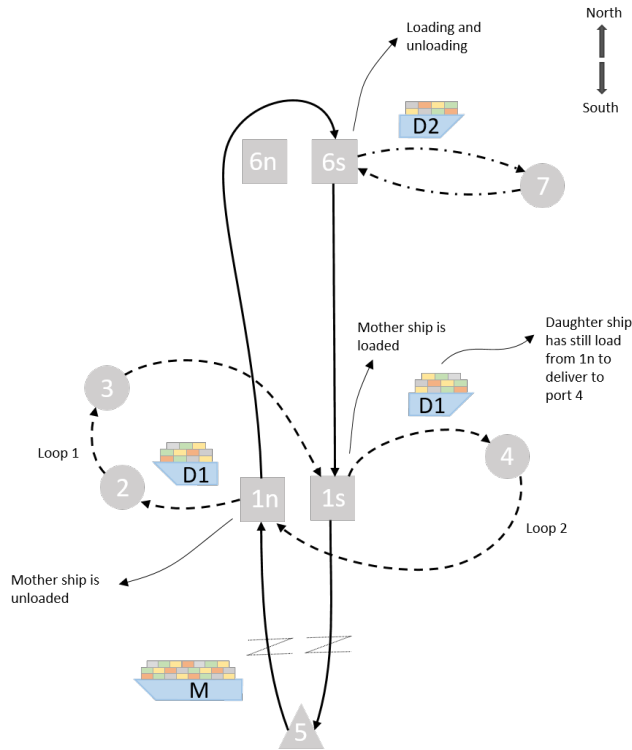


Figure 3.1: Illustration of a feasible solution to the SSP problem. Daughter ship "D1" meets the mother ship "M" twice, while daughter ship "D2" meets the mother once in the northernmost ocean hub.

Daughter ship "D1" receives cargoes from a north-going mother ship in ocean hub 1n. Delivery of cargoes to the mother ship is not possible in this ocean hub. Next, on loop 1, the daughter ship delivers the cargoes at ports 2 and 3 while at the same time picking up cargoes from these ports that are going to the continental main port 5. In ocean hub 1s, the daughter ship delivers the cargoes picked up from ports 2 and 3 to a south-going mother ship. In this case, the daughter ship still has cargoes on board that it received from the mother ship in ocean hub 1n. On loop 2, the daughter ship is therefore delivering these cargoes at port 4 while at the same time picking up cargoes at this port. The cargoes picked up from port 4 will be delivered next time the daughter ship meets a south-going mother ship in ocean hub 1s. After visiting port 4, the daughter ship meets a north-going mother ship at ocean hub 1n to repeat its cycle.

Since ocean hub 6 is the northernmost port on the main route a daughter ship "D2" only meets a mother ship once at this ocean hub port. The daughter ship both loads and unloads cargoes to and from a mother ship. Next, the daughter ship delivers and picks up cargoes at port 7, before it returns to ocean hub 6s and repeats its cycle.

3.2 Effects of Weather Uncertainty

Without any uncertainty, the SSP problem can be solved deterministically. This means that all input data to the problem are known with certainty. In reality, however, this is not the case. An important source of uncertainty is related to weather conditions. With a deterministic SSP problem, the ships are modeled to sail at design speed, but in reality, harsh weather may force the ships to slow down. Not taking the effects of varying weather conditions into account might cause severe problems for the SSP logistics system.

The time usage for a ship on a route can roughly be divided into three parts: *sailing time*, *cargo handling time* and *idle time*. Idle time on a route occurs because the ships might have to wait for each other before a transshipment. In addition, some routes might take shorter time to complete than the maximum allowed duration and since a port can be served only once a week, a ship sailing a route with shorter duration will have idle time.

The daughter ships are expected to be present in the ocean hubs before the mother ship and hence they have to wait to perform a transshipment. The mother ship is expected to arrive in the continental main port before the maximum allowed duration and hence it has to wait before starting to sail its route the next week. This expected waiting time, for both mother and daughter ships, is called *planned idle time*.

The sailing time is calculated based on expected weather conditions and thus, delays will occur each time the weather is worse than planned. This means that the ships must utilize some planned idle time for sailing. Consequently, with too little idle time, the ships might not be able to complete their route within the maximum allowed duration.

In conventional container shipping, there is a need for a schedule that states explicitly when a ship will arrive in a port. Even though this is how ports currently operate, this Master's thesis is focusing on a case in which coastal ports are always open and available to dock a ship whenever it arrives. Only the continental main port must be visited within a strict time window. This is in accordance with the conceptual outline of the SSP logistics system that NCL foresees in the future. For this reason, the timing of coastal port visits is not a primary concern, even though storage time in ports and hence inventory costs might be increased if cargoes must wait in a port longer than expected.

Due to the importance of transshipments at sea, the consequences of a delay can have cascading effects. In the SSP logistics system, the synchronization between a mother and daughter ship during a transshipment may amplify a delay that has occurred due to harsh weather. This is because if one ship is delayed, it might cause other ships to wait before a transshipment can be done. In this way, one single delay can propagate and lead to delays for other ships in the system as well. Clearly, transshipments in ocean hubs are important to analyze when taking effects of harsh weather into account.

When a transshipment in an ocean hub takes place, both the mother ship and the daughter ship have to be present at the same time. If the daughter ship has to wait for the mother ship by more than its planned idle time or the mother ship has to wait for the daughter ship, this is referred to as a *synchronization violation*. When this happens, the ship that is waiting also gets delayed and clearly, a single delay

can propagate and lead to delays for the other ships in the system. Because of this, the transshipments in the ocean hubs are important to analyze when taking weather uncertainty into account.

If a ship gets too delayed, it might be unable to complete its route within the maximum allowed duration. This is called a *duration violation*. As a consequence, not all ports are visited weekly. When a duration violation occurs, a delay will be transferred into the next week, which is highly unwanted. Therefore, for the SSP logistics system to be viable in practice, duration violations should be avoided. To summarize, a duration violation is caused by a delay due to harsh weather conditions which might be amplified because of synchronization violations.

Different methods for finding solutions to the SSP problem with a low number of duration violations at an acceptable cost level is a primary concern covered in the next chapters.

Example

Figure 3.2 illustrates a possible solution to the SSP problem. It consists of a mother ship "M" and two daughter ships "D1" and "D2". Daughter ship "D1" visits both a north-going and a south-going ocean hub, while daughter ship "D2" only meets the mother ship once a week in the northernmost ocean hub. For simplicity, coastal ports and the continental main port are not shown.

In the figure, a green colored ocean hub illustrates that no synchronization violation occurs. A red colored ocean hub illustrates that a synchronization violation occurs.

A blue arrow denotes planned idle time. A yellow arrow denotes planned idle time that must be utilized for sailing because of a delay. A red arrow denotes idle time that occurs because a ship must wait due to a synchronization violation. A red exclamation mark indicates that a duration violation has occurred.

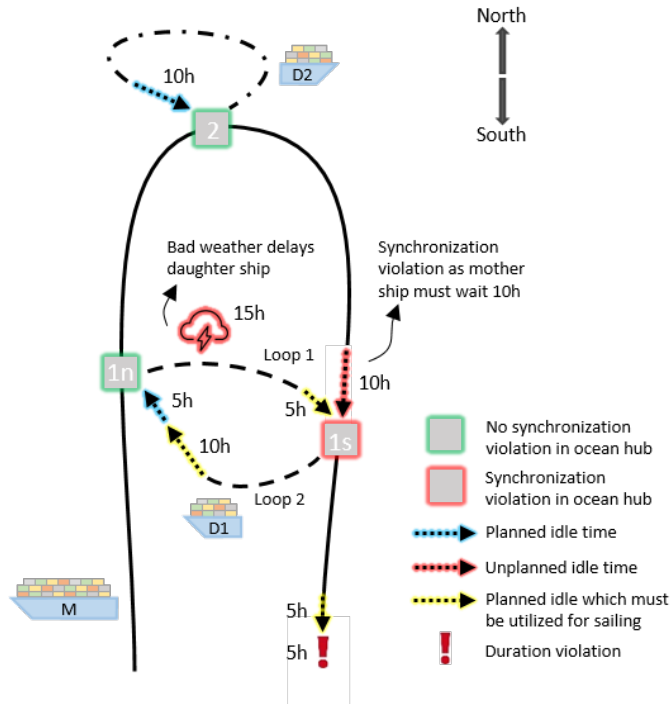


Figure 3.2: Duration and synchronization violations due to harsh weather.

Consider the following scenario, starting in ocean hub 1n. Here, the mother ship and daughter ship "D1" meet in a north-going ocean hub. Neither of the ships are delayed at this point.

For the mother ship, no disruptions occur between ocean hubs 1n and 2, and it is able to synchronize with daughter ship "D2" in the northernmost ocean hub. This daughter ship has 10 hours of planned idle time which means that it could be up to ten hours delayed and still be able to synchronize with the arriving mother ship.

Next, the mother ship continues to ocean hub 1s to synchronize with daughter ship "D1". During loop 1, daughter ship "D1" gets a delay of 15 hours due to harsh weather. Since it has only five hours of planned idle time on loop 1, it is only able to mitigate five hours of the disruption. As of this reason, the mother ship must wait for the daughter ship for 10 hours, and hence it is a synchronization violation on loop 1.

Since daughter ship "D1" is only able to mitigate five hours of the 15 hour weather delay, it is still ten hours late after the synchronization with the mother ship. However, due to idle time on loop 2, it is able to catch up the ten hour delay before the synchronization in ocean hub 1n.

The mother ship has only five hours of planned idle time available to mitigate its 10 hour delay before reaching the continental main port. Thus the mother ship is unable to complete its route within the maximum allowed duration and therefore, a five hour duration violation is incurred. This prevents a weekly port visit frequency, and when the mother ship starts on its next round trip it will be five hours delayed. Avoiding duration violations is therefore critical.

Chapter 4

Literature Review

Maritime transportation problems such as ship routing and scheduling have been widely studied and the number of published research articles has almost doubled every decade (Christiansen et al., 2013). This chapter gives a review of literature relevant for analyzing the SSP problem in an optimization related context.

In Section 4.1, a rather broad scope of topics are briefly presented in order to give insight into how some defining characteristics of SSP problem can be addressed. Based on this, a more narrow selection of research is outlined. In Section 4.2, literature on network design is reviewed. Literature relevant for disruption management with a focus on robust planning and recovery strategies are discussed in Section 4.3. Section 4.4 covers solution methods in general with regards to path flow and arc flow considerations, as well as the use of simulation in maritime shipping problems.

For a more general review on maritime shipping as a whole, the reviews by Christiansen et al. (2013), Christiansen et al. (2007), Christiansen, Fagerholt and Ronen (2004) and Ronen (1993, 1983) are recommended.

4.1 Classification of Shipping Problems

Shipping Modes

Lawrence (1972) describes three general modes of operation in maritime shipping. In *liner shipping*, vessels follow a set of routes according to a published schedule that is fixed for a longer period, typically several weeks or months. The vessels are operated comparable to a public bus service. In *tramp shipping*, the vessels are operated according to cargo contracts. The routes are not fixed, and can change based on which contracts that are chosen, similarly to a taxi service. In *industrial shipping*, an industrial operator controls the vessels and owns the cargoes.

The SSP logistics system can be compared with liner shipping since the ships are supposed to follow routes repeatedly according to a fixed published schedule. In addition, the cargoes to be transported are containerized, which is often the case in liner shipping (Meng et al., 2014).

Planning Levels

Shipping problems are often categorized as being on a strategic, tactical or operational planning level. Although comparable, this categorization can be ambiguous and it usually differs slightly in the literature. [Christiansen et al. \(2007\)](#) present a general categorization applicable for a broad range of shipping problems. [Meng et al. \(2014\)](#), [Agarwal and Ergun \(2008\)](#), [Kjeldsen \(2011\)](#) and [Polat, Günther and Kulak \(2014\)](#) present planning level classifications specifically for liner shipping. A selection of relevant elements in all these frameworks are shown in [Figure 4.1](#) and forms the baseline for further discussion.

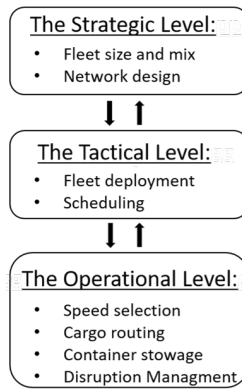


Figure 4.1: A possible categorization of planning levels in maritime shipping.

The strategic planning level deals with the overall long-term decisions with a typical time frame of several years. The *fleet size and mix* problem is concerned with the type and number of ships that a shipping company keeps in its fleet ([Meng et al., 2014](#)). Typically, a fleet of ships can have a lifespan of about 20 to 30 years and acquiring ships can be a long term capital intensive investment. The problem of choosing which routes to serve is usually referred to as a *network design problem* ([Christiansen et al., 2013](#)). The selection of routes is closely related to port selection and visit frequency.

At the tactical level, decisions typically lasting for several months are made, such as seasonal scheduling of liner routes. *Scheduling* is important in order to plan arrival and departure times in ports such that shipping operations can be performed in a timely manner. The *fleet deployment* problem is about assigning ships to routes and is closely related to scheduling. The number of ships deployed on a route forms the basis of the port visit frequency that can be offered to costumers. Most liner shipping companies offer a weekly visiting frequency ([Plum et al., 2014](#); [Brouer et al., 2014](#)).

At the operational level, short term decisions are made, even down to the time scale of hours and days. *Speed selection* is about choosing the sailing speed of the vessels. Since fuel costs account for a major share of operational costs ([Ronen, 2011](#)), speed selection can be important. *Cargo routing* deals with how cargo should be transported across routes from an origin port to a destination port. Related to cargo routing is the problem of *container repositioning* which deals with how empty containers can be transported to where they are needed. Further, *container stowage* deals with how containers should be positioned on board a vessel. Sufficient container stowage avoids

unnecessary cargo handling and ensures that cargoes are properly placed on board a ship.

Another category of operational problems is related to *disruption management*. Being able to handle disruptive unplanned events that occur on a voyage can be crucial in order to mitigate delays and maintain customer satisfaction.

It is important to remember that the different planning levels cannot be separated completely from each other. Decisions made on each level affect the others. The interplay between the different planning levels must often be considered in an integrated problem. This is perhaps an important reason for a rather vague distinction between different planning levels.

For the SSP problem, network design is fundamental to consider and closely related to fleet size and mix, fleet deployment, scheduling and cargo routing. Furthermore, disruption management is highly important in order to take the effects of harsh weather conditions into account. For this reason, both network design and disruption management are examined more in detail in the next two sections.

4.2 Network Design

In this section, problems related to maritime network design are discussed with a focus on liner shipping. In this regard, [Tran and Haasis \(2015\)](#) define the liner shipping network design problem (LSNDP) as the problem of how to select ports and combine them economically to create an infrastructure for shipping operations. A more specific definition is given by [Thun, Andersson and Christiansen \(2016\)](#) who describe the problem as designing a set of cyclic routes for container vessels to provide transportation of goods from origins to destinations.

The LSNDP is a complex problem to solve and [Agarwal and Ergun \(2008\)](#) and [Brouer et al. \(2014\)](#) prove it to be NP-hard. Typically, a LSNDP has no depots which ships must originate from and return to. A ship can traverse a route multiple times and it rarely becomes empty. Such characteristics make the problem difficult compared to more well-known vehicle routing problems and multicommodity flow problems. The LSNDP is thoroughly studied by [Andersen, Madsen and Stidsen \(2010\)](#) who approach the problem by using different multicommodity flow models. By doing this, several challenging characteristics of the problem are addressed, especially with regards to transshipments.

Network design problems are often categorized according to properties of the network. [Thun et al. \(2016\)](#) point out that due to the complexity of the LSNDP, it is common to make assumptions regarding the structure of the network design. For instance, some networks include none or few hub ports, while other networks are more complex.

In general networks, there is no predetermined separation between hub ports and feeder ports. This creates a large number of possibilities for routing and cargo flow. [Agarwal and Ergun \(2008\)](#) consider a network in which transshipments are allowed, and a weekly port visit frequency is required. Their model does not include transshipment costs, something which is included by [Álvarez \(2009\)](#) in a joint routing and fleet deployment problem. However, transshipment costs occurring within a single route are not accounted for, and a weekly port visit frequency is not imposed. [Brouer et al.](#)

(2014) develop the model to capture transshipment costs within a single route. In addition weekly or biweekly visiting frequencies are required.

Reinhardt and Pisinger (2012) present a mixed-integer programming (MIP) model with arc flow formulation that accounts for transshipments as well as transshipment costs. They allow a mix of single routes and butterfly routes. Butterfly routes are defined as routes that visit a port twice. The model is solved exactly using a branch and cut method.

In some networks, only a dedicated set of ports are suitable as hub ports. Meng and Wang (2011) exploit such networks by introducing the concept of segments defined as a pair of ordered ports served by one shipping line. The segments are combined into sets of allowed paths that cargoes can follow. By doing this, specific requirements can be incorporated in the cargo routing constraints. An important aspect in their model is to take container repositioning into account. Zheng, Meng and Sun (2015) also use a segment based approach, but in a slightly different way where the cargo paths are more explicitly modeled. Both models allow for shipping of cargoes either through a hub or directly between ports.

Thun et al. (2016) formulate a model that allows for multiple port visits and few limitations when it comes to network structure. They use a branch and price method to solve the model. The master problem coordinates services and transshipments while the subproblem generates new promising services. By using the model to compare different network structures, they conclude that complex network design can create more cost-efficient networks even for small-sized instances.

Even though several models allow transshipment, synchronization of transshipments in liner shipping network design does not seem to be a focus point in literature. Typically, cargo routing constraints make sure that if a cargo is unloaded at an intermediate port, it must also be picked up again. However, the time a cargo is waiting at a port is not of importance as long as it reaches its destination within time.

Both Brouer et al. (2014) and Agarwal and Ergun (2008) use a space-time graph in their models which potentially could be exploited to allow for synchronizations. However, a space-time graph increases extremely in size if the time interval in which a synchronization must occur becomes small. Zheng et al. (2015) use a continuous time model to assure that cargoes on a specific path are delivered within a required upper time limit. They ignore cargo waiting time at a transshipment port.

Bredström and Rönnqvist (2008) solve a vehicle routing problem with time windows and pairwise precedence and synchronization constraints between customer visits. Synchronization constraints are added to a subset of nodes in which two vehicles must meet at the same time. Within maritime shipping, Andersson, Duesund and Fagerholt (2011) build on this principle to solve a tramp shipping problem with cargo coupling and synchronization constraints. As opposed to Bredström and Rönnqvist (2008), they do not implement synchronization constraints with equality, meaning that some delay within a given time window is allowed. Several exact solution methods are tested, and the best results are obtained by using a column generation approach with modified synchronization constraints in the master problem. Later, Stålhane (2013) improves computational effort by proposing a branch and price approach with the synchronization constraints in the subproblem.

4.3 Disruption Management

Disruption management is a widely used term in the literature and can be defined as “*the need to dynamically revise the original plan and obtain a new one that reflects the constraints and objectives of the evolved environment while minimizing the negative impact of the disruption*” (Yu and Qi, 2004). The authors argue that disruptions, which cause a system to deviate from its original plan, are a result of revealed uncertainty. The uncertainty can originate from various sources, both internal and external. These sources are further classified as changes in the system environment, unpredictable events, changes in system parameters, changes in the availability of resources, new restrictions, uncertainties in system performance and new considerations.

Qi (2015) makes a distinction between two main categories of uncertainties: *recurring and regular uncertainties* and *rare and irregular uncertainties*. The distinction is based on the frequency and significance of the uncertainty, where the former can be anticipated based on historical data, while the latter is impossible to anticipate. The author argues that the impact of regular uncertainties can be proactively incorporated in an operational plan. However, this can not be done for irregular uncertainties, and in accordance with Yu and Qi (2004), real-time management must be applied.

When disruptions occur, it becomes important to reduce their negative implications. Kohl et al. (2007) present a thorough study of disruption management within the airline industry, and three objectives for disruption management are introduced:

1. Deliver the customer promise
2. Minimize the real costs
3. Get back to the plan as soon as possible

Even though these objectives are formulated in an airline industry context, they are still relevant to disruption management in liner shipping.

Possible ways to manage disruptions in liner shipping and the economical implications of delays are discussed in Notteboom (2006). An East Asia - Europe route is considered and the sources of disruptions with their corresponding significance are summarized in Figure 4.2.

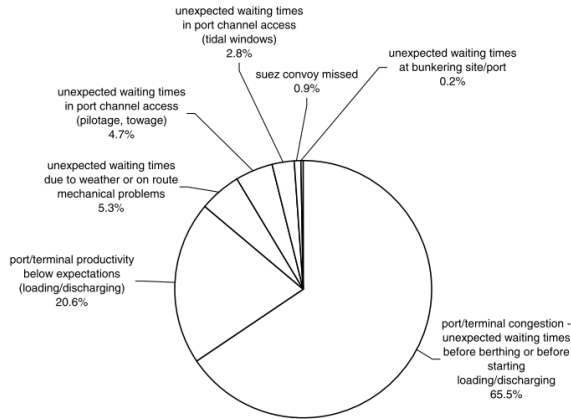


Figure 4.2: Sources of delays on a route from East Asia to Europe. Image from [Notteboom \(2006\)](#).

The expenses of all delays on the trade route are considered and broken down to opportunity cost and depreciation of the containerized goods. Based on this, the economic implications of a one day delay of a full 4,000 TEU container ship from the Far East to Belgium is estimated to be at least 57,000 Euro.

The economic implication of delays in liner shipping is also studied by [Kjeldsen \(2011\)](#) who argue that the costs must be considered on two fronts. In the first place, there are direct costs related to, among else, increased bunker consumption and chartering of additional ships needed for re-planning. In addition, there are intangible costs like loss of goodwill that must be considered by a shipping company.

To avoid expensive delays, uncertainties causing disruptions must be handled by disruption management. Two main strategies are *robust planning* and *recovery strategies*. The former accounts for regular uncertainties and the goal is to create routes inherently less sensitive to disruptions, meaning they are more robust. The latter increases operational flexibility and are typically applied first after a disruption occurs. In the following, both robust planning and recovery strategies in liner shipping are reviewed.

4.3.1 Robust Planning

[Yu and Qi \(2004\)](#) present robust planning as a way to handle uncertainty. In such an approach, the goal is to create an original plan which can be carried out even if disruptions occur. The authors present the following stepwise plan as a robust planning process:

1. Identify the potential disruptive scenarios
2. Choose a robustness criterion appropriate for the decision maker
3. Incorporate the above information and measure in planning to generate a robust plan
4. Carry out the plan without any change no matter what may happen in the future

A robust plan mitigating the worst possible scenario might become too conservative if the worst case scenario is associated with a low probability. Consequently, [Yu and Qi \(2004\)](#) argue that a robust solution might still be subject to change when it is executed.

Several different robustness strategies can be used to protect ship schedules from uncertainty. [Christiansen and Fagerholt \(2002\)](#) study a problem concerned with pick-up and delivery of bulk cargoes within given time windows. The ports are closed during nights and weekends, and an arrival is considered risky if it leads to a departure close to the end of the last time window before the weekend. By penalizing risky arrival times, robustness is increased. Different penalty functions are tested, and the conclusion is that a higher penalty cost yields higher transportation costs but lower calculated risk cost.

[Fischer et al. \(2016\)](#) encounter a fleet deployment problem in roll-on-roll-off shipping with stochastic disruptions in ports and sailing time. Robustness is incorporated by adding extra sailing time on each sailing leg, rewarding early arrivals in ports, penalizing late arrivals and a combination of those. [Halvorsen-Weare and Fagerholt \(2011\)](#) study a supply vessel planning problem with weather uncertainties. Two of the robustness strategies considered are adding profit rewards for each vessel that sails no more than two voyages per week and adding a penalty cost for cargoes that cannot be delivered.

[Halvorsen-Weare, Fagerholt and Rönnqvist \(2013\)](#) study a real-life LNG ship routing and scheduling problem with uncertainty in sailing times due to changing weather conditions and LNG production rates. The authors highlight a problem with adding slack to a schedule which is originally close to being fully utilized. In this case, the original planning problem might become infeasible and it is suggested to reduce the extra slack until the schedule is feasible. In addition to adding slack, they also consider two robustness strategies regarding inventory levels and berth capacity. If inventory levels are outside a soft resource window, penalty costs are assigned. Similarly, penalty costs are assigned if a berth becomes critically utilized.

Robustness strategies based on slack reallocation and delivery separation are examined by [Zhang et al. \(2015\)](#). They study a robust maritime inventory routing problem with flexible time window allocation and stochastic travel times. Idle time is evenly allocated in a space-time network where a travel time arc can be extended with a waiting time arc at a slightly lower cost. This makes it more attractive to include arcs with wait time and thus robustness can be increased without adding too much slack. The strategy of separating consecutive deliveries is based on the rationale that a disruption could cause significant problems when deliveries are clustered together during a short time frame at a port. The authors argue that such deliveries should be separated by a minimum number of time periods.

4.3.2 Recovery Strategies

[Brouer et al. \(2013\)](#) discuss how different disruption management techniques from the airline industry can be adapted to liner shipping. The conclusion is that swapping port calls, omitting port calls and permitting speed-ups can be promising recovery techniques for liner shipping. However, a complicating factor in liner shipping is that ships operate 24 hours a day and cannot utilize overnight slack such as in the airline

industry. A vessel schedule recovery problem is considered and the authors present a MIP-model for handling disruptions. The work is based on the Master's thesis of [Dirksen \(2011\)](#). A given disruption scenario is evaluated and a recovery action is selected based on a trade off between increased bunker consumption, impact on cargo deliveries and also the customer service level.

Whether permitting speed-ups is considered a re-planning action or an operational adjustment that does not need to be explicitly modelled differs within the literature. [Fischer et al. \(2016\)](#) implement speed-up as a recovery action that can be used to get a single ship back to schedule. On the other hand, [Zhang et al. \(2015\)](#) and [Christiansen and Fagerholt \(2002\)](#) assume that minor disruptions can be accounted for by speed adjustments that are not modeled.

[Qi \(2015\)](#) extends the work of [Brouer et al. \(2013\)](#) and develops a model able to manage recoveries for multiple vessels after a major disruption. In the model, there are two different decisions. The vessel routing and speed decision, and the container flow routing. The authors point out that the formulation includes two inter-correlated multi-commodity network flow problems, which may be hard to solve for large-scale problems because of the container flow re-routing.

4.4 Solution Methods

4.4.1 Path Flow Versus Arc Flow Models

Many optimization problems related to different kinds of network problems are usually formulated as arc flow or path flow models. This also apply to maritime shipping problems and [Christiansen et al. \(2007\)](#) describe the usage of these modeling approaches in this context. In an arc flow model, routes are typically created by the use of binary variables that indicate if a given arc between two ports is used by a given ship or not. The model combines arcs to construct a solution with optimal routes. In a path flow model, the principle of column generation is utilized where the process of creating routes and combining them is separated. Candidate routes are constructed in a route generation procedure, and a subset of these candidate routes are then chosen by an optimization model referred to as the master problem. For a general and comprehensive overview on column generation and its applications, the reader is referred to [Desaulniers, Desrosiers and Solomon \(2006\)](#).

A route generation procedure and a master problem can interact in different ways. In an *a priori* approach, all candidate routes are generated at first, and then the master problem selects the optimal routes among these. Routes can be enumerated in the route generation procedure, or dynamic programming may be utilized to decrease the number of candidate routes generated. Another approach is to let the route generation procedure *iteratively* create a small subset of candidate routes as they are needed by the master problem.

A path flow formulation is often used for network design problems. For example, [Fagerholt \(1999\)](#), [Agarwal and Ergun \(2008\)](#), [Álvarez \(2009\)](#), [Meng et al. \(2014\)](#) and [Zheng et al. \(2015\)](#) use this approach for solving network design problems. A path flow formulation is often chosen because the potentially great decrease in solution time compared to using an arc flow model. One reason for this is related to the sub-tour

elimination constraints often required in arc flow models that make these models hard to solve for larger instances. Another important reason is related to the fact that the LP-relaxation of a path flow model typically yields tighter bounds in the branch-and-bound tree.

4.4.2 Simulation and Optimization

A simulation model is suitable for representing how modeled solutions perform in real world conditions. With a simulation model, stochastic aspects and advanced mathematical relations can often be treated properly, as opposed to an optimization model, where this quickly becomes too complex to handle. However, a shortcoming by using a stand-alone simulation model is that underlying routing and scheduling decisions often have to be simplified or omitted (Fagerholt et al., 2010). The different characteristics between simulation and optimization suggest that the methods can be combined. In a general setting, Fu (2002) and Amaran et al. (2014) provide comprehensive overviews on the topic of simulation and optimization with related applications.

Within the more specific setting of maritime shipping, the use of simulation and optimization has received attention in recent literature. In the supply vessel planning problem studied by Halvorsen-Weare and Fagerholt (2011) a simulation model is used to evaluate the robustness of a set of pre-generated routes. Fagerholt et al. (2010) consider strategic planning problems in industrial and tramp shipping with stochastic demand. Their model framework uses a rolling horizon heuristic on a set of demand scenarios. In the roll-on-roll-off fleet deployment problem considered by Fischer et al. (2016), a rolling horizon heuristic is utilized comparably. An optimization based re-planning procedure is triggered based on information gained from simulation. Similarly, in the LNG ship routing and scheduling problem presented by Halvorsen-Weare et al. (2013), an optimization based re-planning procedure is used in a simulation framework. A set of pre-generated solutions are simulated, and the re-planning procedure is called to improve the solutions if certain critical conditions are met.

Chapter 5

Solution Framework

In this chapter, the solution framework for the SSP problem is introduced. To solve the SSP problem deterministically, an optimization model consisting of a master problem and a route generation procedure is used. The optimization model is combined with a simulation model to take weather uncertainty into account.

For a detailed description of the master problem, the route generation procedure and the simulation model, the reader is referred to Chapter 6, 7 and 8, respectively.

Section 5.1 outlines how solution performance can be measured. In Section 5.2, a solution framework for the SSP problem is introduced. In Section 5.3, strategies for increasing robustness and enhancing operational flexibility are discussed. Finally, a list of assumptions are stated in Section 5.4.

5.1 Evaluating Solution Performance

In this section it is discussed how operational cost relates to solution performance.

5.1.1 Operational Cost and Duration Violations

When solving the SSP problem deterministically, all input data to the problem are known with certainty. In that case, a solution with high performance has a corresponding low operational cost. Typically, these solutions have one or several routes with a critically low amount of planned idle time. The low amount of planned idle time makes the solutions highly utilized and cost-efficient in a deterministic setting, but when uncertainty is taken into account, such solutions might be prone to delays.

As described in Subsection 3.2, weather uncertainty can cause delays leading to synchronization and duration violations. This makes it troublesome to operate with weekly and reliable port visits and can cause negative implications for the shipping company such as lost goodwill, loss of customers and extra re-planning costs.

A shipping company could be willing to accept an increase in operational cost if this can reduce duration violations. Effectively, the shipping company could be willing to pay for increased *robustness*. With regards to the SSP problem, this means that the solutions are inherently well suited against duration violations. As an example, NCL might be willing to deploy an additional mother ship to increase slack on the main route, even though this would incur a higher time charter cost.

In addition to increased robustness, another way of reducing the impact of duration violations is to allow for *operational flexibility*. With operational flexibility, real time

management can be used to adjust a plan if a duration violation is about to happen or has occurred. Re-planning and recovery strategies, as described in Chapter 4, create operational flexibility. As an example, NCL might use a speed-up policy which allows ships to speed up on their routes even though it increases bunker cost.

Together, both increased robustness and operational flexibility may increase operational costs, but this might be acceptable if the impacts of duration violations are satisfyingly reduced. In this regard, an important aspect to consider is the *magnitude* of a duration violation which can be defined as the number of hours by which the total duration of a route is violated. The trade-off between operational costs and the magnitude of duration violations depends on the preferences of a decision maker. In practice, for the SSP system to be viable, the magnitude of duration violations should be close to zero.

5.1.2 Using a Penalty Cost to Indicate Solution Performance

A solution to the SSP problem that has low operational costs taking duration violations into account is considered to be of high performance. An issue is then to incorporate how duration violations affect operational costs.

To reflect this issue, a penalty cost based on the magnitude of duration violations is added. The penalty cost determines how duration violations should be weighted in the total cost expression. By including a penalty cost, the resulting total cost expression would make solutions prone to duration violations less attractive when solving the SSP problem.

It can be hard to determine how much duration violations should be penalized as the consequences of duration violations are difficult to relate to direct costs. However, a penalty cost value can be based on preliminary testing. Even though the penalty cost per se is fictional, it represents that solutions prone to duration violations are not considered high performing.

5.1.3 The Collective Properties of a Solution

When referring to a solution to the SSP problem, it is emphasized that a solution consists of a combination of routes. Ultimately, it is the *collective* properties of the routes in a solution that determines its performance. It is therefore important to be careful about evaluating routes individually. Conceptually, a route with seemingly poor performance due to high costs might be attractive if the route enables other low-cost routes to be part of a solution.

5.2 Optimization-Simulation Framework

For the SSP problem, a column generation approach is chosen as it is often used for network design problems as explained in Section 4.4. With this approach, a master problem selects solutions based on a set of candidate routes generated by a route generation procedure. To incorporate effects of weather uncertainty, a simulation

model is used to evaluate real world performance of solutions proposed by the master problem.

When solving the SSP problem the master problem is solved for each daughter ship type available and the rationale behind this is explained in Chapter 6. A simplistic approach for finding well performing solutions would be to only solve the master problem once for each daughter ship type and then simulate the resulting solutions. To improve performance, different strategies to enhance robustness and operational flexibility could be applied. However, since the master problem would only be solved once for each daughter ship type, few solutions would be simulated. Consequently, other, potentially better solutions would not be found. This drawback can be avoided if larger parts of the solution space are simulated.

A naive way to consider larger parts of the solution space, is to simulate all solutions to the SSP problem. However, with a large number of possible solutions, this becomes computationally impossible. Only a set of the most promising solutions should therefore be considered. It can be difficult to determine this set a priori and still guarantee to find the best performing solutions. This suggests the use of an iterative feedback process between the master problem and the simulation model.

The flow chart in Figure 5.1 provides an overview of how the route generation procedure, the master problem and the simulation model are related when solving the SSP problem. This framework is in this Master's thesis referred to as the *optimization-simulation framework* and the feedback process is referred to as the *solution triggered feedback approach*.

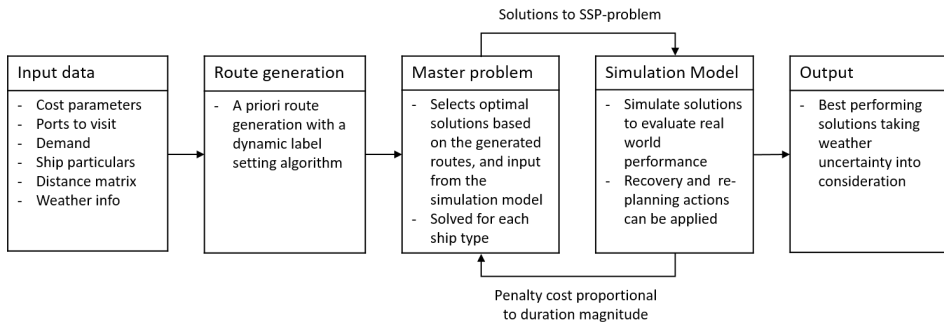


Figure 5.1: Flow chart giving a brief overview of the optimization-simulation framework with solution triggered feedback.

In the framework, provided input data are used to generate a set of routes in the route generation procedure. This set of routes are then sent to the master problem. Solutions from the master problem are simulated taking weather uncertainty into account. In the simulation model, different strategies for handling weather uncertainty can be applied. A penalty cost is added to a simulated solution proportionately to the magnitude of duration violations. The master problem can then be resolved with updated cost information. This enables the master problem to select other solutions with potentially lower total costs. The iterations between the master problem and the simulation model continue until no new better solutions are found.

5.3 Strategies for Handling Weather Uncertainty

Solutions found by the solution triggered feedback framework from the previous section might be improved by applying different strategies for improving robustness and/or operational flexibility.

5.3.1 Adding Slack

A common approach to improve robustness is to add extra sailing time to a route. This extra sailing time acts as a buffer for potential delays and can be referred to as slack. For the SSP problem, slack can be added in the route generation procedure. When slack is added to a route, the planned idle time is reduced and hence each sailing leg is considered more time-consuming. If the weather conditions are better than anticipated not all the slack added to a route is needed.

The implications of adding slack can be both positive and negative. By adding slack, routes with too little amount of idle time, which are prone to disruptions, are removed from the solution space. Thus, the remaining routes can be considered more robust. On the other hand, finding the correct values of slack to add can be difficult, resulting in deleting potential high-performing routes.

Adding slack causes three effects when using the optimization-simulation framework. Firstly, routes may be combined differently resulting in solutions otherwise not possible. This is because the time between ocean hubs visits increases and this may allow for new combinations of routes. Secondly, since routes with too little idle time are removed this reduces computational effort. Thirdly, the magnitude of duration and synchronization violations can be reduced as ships have more time available for sailing before each ocean hub visit. Thus, even if a ship must reduce sailing speed due to harsh weather, it might still be able to synchronize in an ocean hub without any synchronization violations.

5.3.2 Speed-up Policy

A common approach to reduce a potential delay on a route is to increase sailing speed. For the SSP problem, a speed-up policy is implemented based on planned idle time and the time used for sailing. The speed-up policy can be considered a recovery strategy increasing operational flexibility. The speed-up policy is applied in the simulation model, and is based on the criteria presented below.

Without idle time before an ocean hub visit, a daughter ship can potentially cause a mother ship to wait. Therefore, if a delay causes a daughter ship to have less than a minimum amount of idle time, a speed-up is allowed. The speed-up will continue until the amount of idle time is increased to a given level above the minimum idle time.

A delayed mother ship without any idle time before an ocean hub visit will arrive later than planned. This might cause a daughter ships to wait. As of this reason, if a mother ship gets delayed by more than a given amount of time, it is allowed to speed up until it is no longer delayed.

Note that with the given speed-up policy each ship speeds up on an individual basis. That is: the consequence of a delay for a given ship is not checked up against delays of other ships. This creates a speed-up policy which is easy to operate for a shipping company as it reduces the need for communication between ships.

A drawback with the given speed-up policy is that a ship might speed up even if it is not necessary. An unnecessary speed-up might happen if two ships are delayed and only one of them is able to speed up enough to reach the ocean hub in time. In this situation, the ship that has increased its sailing speed enough has also increased its bunker cost. In addition, it must still wait for the ship that is not able to speed up enough.

Even though a speed-up policy can mitigate delays, it incurs extra bunker costs. Together with potential penalty costs, extra bunker costs should be included in the total cost expression when evaluating performance.

5.3.3 Seasonal Routes

With different weather conditions in the summer compared to the winter, it might be beneficial to operate different routes in the summer and winter season. For the SSP Logistic System, it is reasonable to assume that the same fleet should be used both in the summer and winter season.

To incorporate seasonality effects, solutions for the winter season and the summer season are found separately. To do this, a solution for the summer season is simulated and evaluated over the summer months, while a winter solution is simulated and evaluated over the winter months. When combining summer and winter solutions, it is important that the same number of ships as well as the same size of the daughter ships are chosen. Thus, one must make sure that a given fleet configuration in one season is found for the other season as well. Only the route configuration is allowed to change from one season to another.

After a winter and summer solution with the same fleet configuration is found, the costs can be added together. The cost for the whole year is then the average of the costs for the summer solution and winter solution.

With the opportunity of using a tailor made solution for the summer and winter season, the total cost is always lower or equal to the cost of using the same configuration for the whole year. This is because the set of routes in a seasonal solution cannot be worse adapted to the specific weather conditions in the actual season than a solution adapted to the whole year.

5.4 Assumptions

To make it possible to model the SSP problem, some assumptions are needed. The assumptions presented in the following are mainly based on the assumptions given in [Holm and Medbøen \(2016\)](#), but some new assumptions are added with regards to weather uncertainty.

- **A limited number of possible locations for ocean hubs are given.**

Since transshipments are performed at sea, ocean hubs could potentially be located wherever mother and daughter ship can couple together. However, in practice, some locations are more suitable than others based on experience from the shipping operator. The operator will for instance take ocean conditions into consideration when deciding suitable locations. In addition, there is only a negligible difference in choosing between two ocean hub locations that are located close to each other. It is therefore reasonable to assume that only a limited number of possible ocean hub locations are given.

- **A mother ship can adjust its speed to reach each ocean hub in time.**

It is emphasized that this assumption is only affecting the route generation procedure and hence it has no implications for the speed-up policy.

When main routes are generated, it must be known for how long time a mother ship will stay in an ocean hub (see Chapter 7). Since all ports must be visited, it is possible to calculate exactly the *total* time a mother ship must spend in ocean hubs at the route generation stage. However, the time spent in each *specific* ocean hub cannot be calculated exactly. This is because it is not known which coastal ports that will be connected to a given ocean hub at route generation stage. As a consequence, estimates of the specific time in each ocean hub must be used, and it must be assumed that a mother ship can adjust its speed to reach each ocean hub in time. With long distances between each ocean hub and with a fairly even distribution of the amount of cargoes that are transshipped at each ocean hub, this can be a reasonable assumption.

To elaborate on this assumption a bit more, consider the example in Figure 5.2.

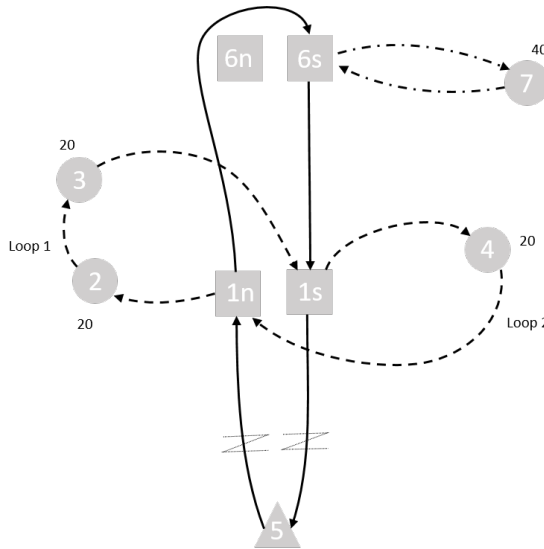


Figure 5.2: Illustration of time estimate in ocean hubs.

The number of cargoes picked up and delivered in each coastal daughter port is shown in the figure. In total, this accounts for 100 cargoes, and with a cargo

handling time of 10 cargoes per hour, the mother ship must spend in total 10 hours on cargo handling.

It is not possible to know exactly how these 10 hours should be distributed among the ocean hubs before daughter routes are selected. This is because each daughter route connects coastal daughter ports to ocean hubs, but the daughter routes are first selected in the master problem. For instance, it is not known at the route generation stage if port 3 should be connected to ocean hub 1 or 6. In the figure, port 3 is connected to ocean hub 1, but this is a result that becomes clear when routes are selected after the route generation stage.

For the estimate of how long time a mother ship uses in an ocean hub, it is assumed that the same amount of cargoes are transshipped in an ocean hub visited once, as in an ocean visited on both the north-going and south-going part of the main route. In the figure, ocean hub 1 is visited twice and ocean hub 6 is visited once. Following the assumption, the same amount of cargoes is handled in the two ocean hubs and thus, the estimated cargo handling time in ocean hub 1 as well as in ocean hub 6 is $10/2 = 5$ hours. Further, it is assumed that the same amount of cargoes are transshipped in a north-going and south-going ocean hub. This implies that $5/2 = 2.5$ should be used in both ocean hub 1n and ocean hub 1s.

However, if the two daughter routes in the figure are chosen as a solution to the problem, then a total of 6 hours are needed in ocean hub 1n and 1s and 4 hours are needed in ocean hub 6s. To compensate for the deviation between the actual needed time in each ocean hub and the estimate, it must be assumed that a mother ship can adjust its speed to reach each port in time.

- **Requirements for the main route.**

NCL has expressed that they overall transport more cargoes to the Continent than from the Continent. A mother ship is therefore assumed to only visit coastal main ports when sailing south. This is most beneficial in terms of average transit time. In addition, it is also assumed that if a mother ship visits a north-going ocean hub, then the corresponding south-going ocean hub must also be visited. This is to reduce the complexity of the route structure.

- **If a daughter ship meets a mother ship twice, the meeting location must be at the same ocean hub.**

This is stated in the problem description and reduces the complexity of the route structure.

- **No time windows in coastal ports.**

It is assumed that coastal ports are always open and available to dock a ship whenever it arrives. However, a mother ship cannot depart from the Continental main port before its scheduled departure time as found in the route generation procedure. This is in accordance with the problem description.

- **Weather uncertainty is the only source of uncertainty.**

The focus in this Master's thesis is to study the implications of weather uncertainty. Other sources of uncertainty, like for instance varying cargo demand, are therefore not considered.

Chapter 6

Master Problem Formulation

In this chapter, the master problem is formulated. Section 6.1 presents a master problem formulation for the SSP problem without taking weather uncertainty into consideration. This formulation can be used to solve the SSP problem deterministically. To incorporate the solution triggered feedback approach, a few changes are needed. These changes are presented in Section 6.2, together with a description of how multiple solutions can be found in each iteration between the master problem and the simulation model.

6.1 Master Problem Formulation

In the following, notation for the master problem is defined.

Indices:

- p Port.
- m Main route.
- d Daughter ship route.

Sets:

- \mathcal{P}^{OH} Set of ocean hubs.
- \mathcal{P}^{CD} Set of coastal daughter ports.
- \mathcal{P}^{CM} Set of coastal main ports.
- \mathcal{R}^M Set of main routes. One or two mother ships can serve a main route.
- \mathcal{R}^D Set of daughter routes. A given daughter route d can be served by one and only one daughter ship.
- \mathcal{R}_p^M Set of main routes that includes port p . $\mathcal{R}_p^M \subseteq \mathcal{R}^M$.
- \mathcal{R}_p^D Set of daughter routes that includes port p . $\mathcal{R}_p^D \subseteq \mathcal{R}^D$.
- \mathcal{R}_{pm}^D Set of daughter routes that includes port p and is synchronized to a main route m . $\mathcal{R}_{pm}^D \subseteq \mathcal{R}_p^D \subseteq \mathcal{R}^D$.

Note that a port cannot be of more than one type, i.e. $\mathcal{P}^{OH} \cap \mathcal{P}^{CD} = \emptyset$, $\mathcal{P}^{OH} \cap \mathcal{P}^{CM} = \emptyset$ and $\mathcal{P}^{CD} \cap \mathcal{P}^{CM} = \emptyset$.

The set of ocean hubs \mathcal{P}^{OH} can include both south-going and north-going ocean hubs specifically, but there is no need for such a split. However, this distinction is necessary in the route generation procedure.

To explain the set of daughter routes that includes port p and is synchronized to a main route m , \mathcal{R}_{pm}^D , a bit more, consider Figure 6.1. In this figure, a main route m_1 is shown. The main route includes continental main port 5, and one south and north-going ocean hub, 1n and 1s, respectively. The main route m_1 is one of many potential main routes generated in the route generation procedure. For simplicity, assume that only one mother ship is deployed on this particular main route. The mother ship arrives at ocean hub 1n at time t_1 , and it arrives at ocean hub 1s at time t_2 . In addition to the main route, two daughter routes, d_1 and d_2 are shown. These two daughter routes are suitable of being synchronized with the main route in order to meet the mother ship in hub 1n and 1s at time t_1 and t_2 , respectively.

Since both d_1 and d_2 include ocean hub 1, these daughter routes belong to the set $\mathcal{R}_{p=1,m_1}^D$. Further, since both d_1 and d_2 include coastal daughter port 4, they also belong to the set $\mathcal{R}_{p=4,m_1}^D$. Daughter route d_1 includes coastal daughter port 2, and it belongs to the set $\mathcal{R}_{p=2,m_1}^D$. Similarly, d_2 belongs to the set $\mathcal{R}_{p=3,m_1}^D$.

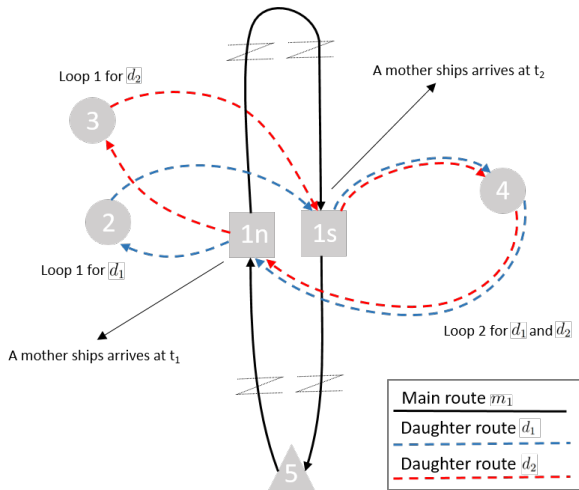


Figure 6.1: Two daughter routes that are synchronized with a given main route.

A daughter route $d \in \mathcal{R}_{pm}^D$ might not necessarily include two ocean hub visits since an ocean hub which is the northernmost point on a main route is only visited by a daughter ship once as described in Chapter 3.

The parameters used in the master problem formulation are described in the following.

Parameters:

- Q^V Daughter ship cargo capacity.
- Q_d^D Cargo capacity needed to serve a daughter route $d \in \mathcal{R}_d$.
- C_m^M Total cost of using a fleet of mother ships on a main route $m \in \mathcal{R}^M$. It includes a weekly time charter cost, bunker costs and port costs.
- C^{TC} Weekly time charter cost of using a daughter ship.
- C_d^{OC} Operating cost for a daughter ship deployed on daughter route $d \in \mathcal{R}_d$. It includes port costs and bunker costs.
- M^{OH} Big-M value that sets the upper limit on how many daughter ships that can visit an ocean hub $p \in \mathcal{P}^{OH}$. If M^{OH} is set to 1, then an ocean hub can be visited by maximum one daughter ship.

Note that the parameters Q_d^D , C_m^M , and C_d^{OC} are calculated in the route generation procedure.

Variables:

- x_m A binary variable which takes the value 1 if a mother ship sails main route $m \in \mathcal{R}^M$, and 0 otherwise.
- z_d A binary variable which takes the value 1 if a daughter ship sails daughter route $d \in \mathcal{R}^D$, and 0 otherwise.

With the defined notation, the master problem formulation is presented below.

Objective function:

$$\min \sum_{m \in \mathcal{R}^M} C_m^M x_m + \sum_{d \in \mathcal{R}^D} (C^{TC} + C_d^{OC}) z_d, \quad (6.1)$$

Constraints:

$$\sum_{m \in \mathcal{R}^M} x_m = 1, \quad (6.2)$$

$$\sum_{d \in \mathcal{R}_p^D} z_d - M^{OH} \sum_{m \in \mathcal{R}_p^M} x_m \leq 0, \quad p \in \mathcal{P}^{OH}, \quad (6.3)$$

$$\sum_{d \in \mathcal{R}_{pm}^D} z_d - \sum_{d \in \mathcal{R}_p^D} z_d \geq M^{OH} (x_m - 1), \quad p \in \mathcal{P}^{OH}, \quad m \in \mathcal{R}^M, \quad (6.4)$$

$$\sum_{d \in \mathcal{R}_{pm}^D} z_d - x_m \geq 0, \quad p \in \mathcal{P}^{OH}, \quad m \in \mathcal{R}_p^M, \quad (6.5)$$

$$\sum_{m \in \mathcal{R}_p^M} x_m + \sum_{d \in \mathcal{R}_p^D} z_d = 1, \quad p \in \mathcal{P}^{CM}, \quad (6.6)$$

$$\sum_{d \in \mathcal{R}_p^D} z_d = 1, \quad p \in \mathcal{P}^{CD}, \quad (6.7)$$

$$Q_d^D z_d \leq Q^V, \quad d \in \mathcal{R}^D, \quad (6.8)$$

$$x_m \in \{0, 1\}, \quad m \in \mathcal{R}^M, \quad (6.9)$$

$$z_d \in \{0, 1\}, \quad d \in \mathcal{R}^D. \quad (6.10)$$

The objective function (6.1) minimizes the total weekly cost of operating the transportation system. The first term is the total weekly cost of all mother ships deployed. The second term is the total weekly time charter and operating costs for all daughter ships deployed.

Constraint (6.2) ensures that one and only one main route is used. Even though only one main route is chosen, more than one mother ship can be deployed on the main route if it is required.

Constraints (6.3) to (6.5) connect daughter ship routes to an ocean hub on the main route. This makes sure that every daughter ship can perform a transshipment with a mother ship.

Constraints (6.3) make sure that at most M^{OH} daughter ships can visit a given ocean hub on a selected main route. These constraints also state that if a mother ship does not visit an ocean hub, then no daughter ships can visit the ocean hub.

Constraints (6.4) ensure that if a main route includes an ocean hub, then only daughter routes that can be matched with the given main route can be chosen. Since all daughter routes that can be matched with a given main route m belong to the set \mathcal{R}_{mp}^D , other daughter routes belonging to other main routes cannot be active. This requirement is satisfied if and only if $\sum_{d \in \mathcal{R}_{pm}^D} z_d = \sum_{d \in \mathcal{R}_p^D} z_d$. If a mother ship visits an ocean hub, then the right-hand side of the constraint becomes zero, and the condition can be met. Since it is obviously impossible that the sum of elements in a subset can be greater than the sum of all elements in a corresponding superset, using a greater or equality constraint is possible. If a mother ship does not visit an ocean hub, the constraint becomes redundant.

Constraints (6.5) ensure that if no daughter ships visit an ocean hub, then no main routes that include this ocean hub can be used. These constraints could potentially be excluded if a mother ship was allowed to sail through an ocean hub without meeting a daughter ship. Actually, this would typically not happen anyhow since a main route sailing through an ocean hub is often longer than a main route without the hub. Thus, in these cases, the objective function prevents a mother ship to sail through an ocean hub where no meeting with a daughter ship takes place.

Constraints (6.6) make sure a coastal main port is visited by either a mother or a daughter ship.

Constraints (6.7) assign each coastal daughter port to a daughter ship route to ensure that every coastal daughter port is visited.

Constraints (6.8) make sure that no daughter ships carry more cargoes than the maximum cargo capacity. Note that these constraints are only needed if there exist routes with a higher capacity need than the daughter ship is capable of.

Constraints (6.9) and (6.10) restrict the variables to take binary values.

As explained in the problem description, a mother ship has always enough capacity, and can transport as many cargoes as needed on a main route. Further, since all coastal ports must be visited by a ship that is connected to the main route, and since each daughter ship must have enough capacity to pick up and deliver all cargoes on its route, no explicit cargo flow constraints are needed in the master problem.

The master problem is solved one time for each available daughter ship type. Based on the resulting solutions, the best one can be chosen. This approach is faster than including constraints for ship type selection in the master problem (Holm and Medbøen, 2016) and is manageable to handle since NCL only considers a limited number of ship types. Solving the model iteratively for each ship type gives information about the solutions belonging to each ship type. This information is of interest from a decision maker's perspective as cost differences between ship types can be compared.

6.2 Incorporating Solution Triggered Feedback

The changes needed for the master problem in order to incorporate the solution triggered feedback approach are presented in Subsection 6.2.1. Subsection 6.2.2 describes how a set of the n-best solutions to the SSP problem can be found in each iteration when solving the master problem. Subsection 6.2.3 presents a pseudo code for the solution triggered feedback approach.

6.2.1 Formulation Changes

When a solution is simulated, the simulation model sends information to the master problem about which routes that are included in the solution and the corresponding penalty cost. For simplicity, potential speed-up costs are also referred to as penalty costs.

With the formulation from the previous section, the costs minimized in the master problem are only route specific. Penalty costs, which are dependent upon a specific solution, are therefore not possible to evaluate. A few changes must be made to include such costs by letting a binary variable indicate whether or not a solution has been simulated by the simulation model. If a solution has been simulated, the corresponding penalty cost is added in the objective value to the master problem.

The following notation is defined to incorporate the new changes:

Indices:

- s Simulated solution.

Sets:

- S Set of simulated solutions. If the set is empty, no solutions have been simulated. The size of the set increases for every new solution that is simulated.

Parameters:

- S_{ms}^M Parameter that has the value 1 if a main route m belongs to a simulated solution s , and 0 otherwise.
- S_{ds}^D Parameter that has the value 1 if a daughter route d belongs to a simulated solution s , and 0 otherwise.
- S_s The number of routes which belong to a solution. This can be expressed as follows: $S_s = \sum_{m \in \mathcal{R}^M} S_{ms}^M + \sum_{d \in \mathcal{R}^D} S_{ds}^D$, for each simulated solution s .
- C_s^S The simulated penalty cost of a simulated solution s .
- ε Small value used to express a less than relation as a less than or equal relation. The value can be as small as possible as long as $\varepsilon > 0$.
- M^S Big M-value. The smallest possible value is M^S marginally larger than ε .

The set of simulated solutions \mathcal{S} and the parameters S_{ms}^M , S_{ds}^D and S_s describing the routes belonging to a solution s , is given from the simulation model to the master problem, as well as the corresponding penalty cost C_s^S . The set and parameters from the simulation model is used to trigger an indicator variable y_s , as defined below, if a solution has been simulated.

Variables:

- y_s Binary indicator variable which takes the value 1 if a solution has been simulated, and 0 otherwise.

The objective function is changed by adding the term $C_s^S y_s$ in order to include penalty costs, which are solution specific. The objective function can then be expressed as follows:

Objective function:

$$\min \sum_{m \in \mathcal{R}^M} C_m^M x_m + \sum_{d \in \mathcal{R}^D} (C^{TC} + C_d^{OC}) z_d + \sum_{s \in \mathcal{S}} C_s^S y_s \quad (6.11)$$

In addition new constraints must be added. These constraints are:

Constraints:

$$\sum_{m \in \mathcal{R}^M} S_{ms}^M x_m + \sum_{d \in \mathcal{R}^D} S_{ds}^D z_d - M^S y_s + \varepsilon \leq S_s, \quad s \in \mathcal{S}, \quad (6.12)$$

$$\sum_{m \in \mathcal{R}^M} S_{ms}^M x_m + \sum_{d \in \mathcal{R}^D} S_{ds}^D z_d \geq S_s y_s, \quad s \in \mathcal{S}, \quad (6.13)$$

$$y_s \in \{0, 1\}, \quad s \in \mathcal{S}. \quad (6.14)$$

Constraints (6.12) and (6.13) activate the indicator variable y_s if a solution has been simulated. If the master problem selects a route combination which constitutes a previously simulated solution, the penalty cost is added to the objective.

Constraints (6.12) set $y_s = 1$ if a solution is simulated. Note that Constraints (6.12) effectively express a less than relation since ε is included. Constraints (6.13) prevents that $y_s = 1$ if a solution is *not* simulated. This constraint should be included when more than one solution is obtained in each iteration as explained in the next subsection.

Constraints (6.14) restricts the y_s variables to take binary values.

To explain constraints (6.12) and (6.13) more in detail let $A_s = \sum_{m \in \mathcal{R}^M} S_{m,s}^M x_m + \sum_{d \in \mathcal{R}^D} S_{d,s}^D z_d$. A_s is a short-form of writing the left-hand term in constraints (6.13) and this term is also included in constraints (6.12). Consider the fact that $A_s \leq S_s$ always holds for a given solution s . This is because the parameters $S_{m,s}^M$ and $S_{d,s}^D$ limits the value A_s can take, regardless of the number of routes chosen by the master problem.

If $A_s < S_s$, the number of routes in a solution does not match the number of routes in a simulated solution, thus the solutions cannot be identical. In this case y_s is set to zero and no penalty cost is added.

If $A_s = S_s$ then exactly the same routes are used and the solutions must be identical. In this case y_s is set to 1 and the penalty cost is added. Note that if $A_s = S_s$ the total number of routes chosen by the model $\sum_{m \in \mathcal{R}^M} x_m + \sum_{d \in \mathcal{R}^D} z_d$ cannot be greater than the number of routes in a solution S_s . This is because the continental main port and all coastal ports must be visited exactly once in a solution to the SSP problem, and that there exist no routes which do not include these port types. Thus, two different solutions, in which one of the solutions contains a subset of the routes in the other solution, cannot coexist.

These considerations clarify how one can be sure that a solution is identical to a simulated solution if $A_s = S_s$, and not identical otherwise.

The complete master problem formulation with the changes needed for the solution triggered feedback approach is found in Appendix B.

6.2.2 Finding the n-best Solutions in an Iteration

Originally, in each iteration between the master problem and the simulation model, only one new solution for each ship type is found. However, with some adjustments, the master problem can return a set of solutions for each ship type in each iteration. The rationale behind such an adjustment is to speed up the solution process by reducing the number of iterations needed. Letting the master problem find several solutions in one run is potentially faster than only finding one solution at a time. Also, by reducing the number of iterations, less time is spent on transferring information between the optimization model and the simulation model.

One approach for finding several solutions each time the master problem is solved is to use all solutions found during the branch-and-bound search. However, some of the solutions found can be subject to very high deterministic operational costs, and the number of the solutions found will vary. Another approach is therefore to find the n best solutions in each iteration. With this approach the set of the n solutions with the lowest cost is found. The number of solutions to find in each iteration can be determined based on experience with the specific problem at hand. Setting n too low typically causes many time-consuming iterations. Setting n too high typically means that more solutions than necessary are evaluated. It is emphasized that a good value for n is problem specific. For a discussion of finding a promising n for a given test instance, the reader is referred to Section 10.2 in the computational study.

The possibility of finding more than one solution explains why constraints (6.13) are

necessary. Without these constraints, it would be possible that a solution, even though not simulated, could incorrectly be assigned a penalty cost belonging to another solution.

The solution method used to find a set of the $n > 1$ best solutions is based on enumeration of all possible solutions in the branch-and-bound tree. In the standard branch-and-bound method, only integer restricted variables that are fractional in the current solution are branched on. When finding a set of the $n > 1$ best solutions, even solutions without fractional variables are branched on. Thus a complete enumeration of the branch-and-bound tree is attempted, although greatly speeded up by not solving any sub problem where the bound is worse than the n 'th best solution found so far. It is however emphasized that the speed of the solution method is problem specific and based on the complexity of the model formulation.

Implementing the solution method of finding the n -best solutions has been done in the commercial optimization software Xpress (for details see Section 10.1.4). The solution method is a built-in solution feature in Xpress. Care should be taken in order to disable all preprocessing operations that potentially reduce the solution space. Thus any operations that remove dominated or symmetric solutions must be turned off.

6.2.3 Pseudo Code for the Solution Triggered Feedback

To better understand how the solution triggered feedback approach works, Pseudo Code 1 is presented. It shows how the master problem is solved for each ship type and how the solutions obtained from the master problem is used in the simulation model.

The algorithm starts by taking *ShipTypes* as well as the variable n -best as input. *ShipTypes* defines the ship types to solve for, and n -best gives the number of solutions to find for each ship type in each iteration. Note that each time the master problem is solved for a given ship type, this counts as an iteration.

Initially, *ShipTypesToSolve* is equal to *ShipTypes*. This is a set containing the ship types for which a final solution is not yet found. The set of final solutions, *FinalSols*, as well as the set of simulated solutions, *SimSols*, are initially empty sets. *NIterations* is initialized as 1.

As long as a final solution is not yet found for every ship type, the master problem is solved again. The master problem returns the n -best solutions for a given ship type, in which *OptimalSol* is the solution with the lowest cost among the n -best solutions. If *OptimalSol* is previously simulated, it means that this is the solution minimizing the total cost, including both operational costs and penalty costs. Hence, it is added to the set of final solutions and the ship type is removed from the set of ship types to solve for.

If the final solution for a given ship type is *not* found in the given iteration, all solutions not simulated in earlier iterations have to be simulated. This is done in the simulation model, and the set of simulated solutions is updated. Note that this step corresponds to updating the set \mathcal{S} , and the parameters S_{ms}^M , S_{ds}^D , S_s and C_s^S as defined in Subsection 6.2.1. Lastly, the number of iterations, *NIterations* is incremented.

This iteration process continues until a final solution is found for each ship type. Then, *FinalSols* contains the final solution for each ship type.

Algorithm 1 The solution triggered feedback approach.

```

1: procedure SOLUTIONTRIGGEREDFEEDBACK(ShipTypes, n-best)
2:   ShipTypesToSolve  $\leftarrow$  ShipTypes            $\triangleright$  Set with ship types to solve for
3:   FinalSols  $\leftarrow$   $\emptyset$                         $\triangleright$  Empty set of solutions
4:   SimSols  $\leftarrow$   $\emptyset$                           $\triangleright$  Empty set of simulated solutions
5:   NIterations = 0                                  $\triangleright$  Number of iterations
6:   while ShipTypesToSolve  $\neq$   $\emptyset$  do
7:     for each ShipType  $\in$  ShipTypesToSolve do
8:       (n-sols, OptimalSol) = SOLVEMP(ShipType, n-best, SimInfo)
9:       if OptimalSol  $\in$  SimSols then              $\triangleright$  Final solution is found
10:        FinalSols  $\leftarrow$  FinalSols  $\cup$  OptimalSol
11:        ShipTypesToSolve = ShipTypesToSolve  $\setminus$  {ShipType}
12:      else
13:        SolsToSim = NOTSIMULATEDBEFORE(n-sols, SimSols)
14:        SimSols  $\leftarrow$  SIMULATE(SolsToSim)       $\triangleright$  Extend the SimSols set
15:      end if
16:      NIterations = NIterations + 1  $\triangleright$  Increment the number of iterations
17:    end for
18:  end while
19: end procedure

```

Chapter 7

Route Generation Procedure

This chapter describes the route generation procedure used to generate candidate routes for the master problem presented in Chapter 6. A dynamic label-setting algorithm is used to generate main and daughter routes. Section 7.1 gives a theoretical overview and an introduction to the route generation procedure. The description of main route and daughter route generation is covered in Section 7.2 and 7.3 respectively. The synchronizing of the routes is presented in Section 7.4.

It is emphasized that this chapter is a modified version of the chapter covering the route generation procedure in [Holm and Medbøen \(2016\)](#).

7.1 Introducing the Route Generation Procedure

7.1.1 Theoretical Overview

Using a dynamic programming approach to create feasible routes provides advantages compared to an approach where all possible routes are enumerated. According to [Irnich \(2008\)](#), the efficiency of a dynamic programming approach depends on the principle of *dominance* which is the ability to identify and discard generated paths. A path consists of a sequence of nodes and in the context of this Master's thesis, a path corresponds to a ship route. It can be a partial route which is not complete or a complete route which is fully generated. Enumerating all feasible candidate routes creates a huge number of routes something which is time-consuming considering that some of these candidate routes will be outperformed by other candidate routes having more beneficial properties. By dominating these routes at an early stage, the number of generated candidate routes decreases. This can lead to a reduced computational time, not only for the route generation procedure, but also for the master problem.

The label-setting dynamic programming approach presented in this chapter generates routes a priori, that is: all candidate routes are first generated before the master problem selects optimal routes. Another possibility is to create routes iteratively, but using an a priori method can be easier to implement, and also to understand for a potential decision maker. However, a drawback of using an a priori method is that an iterative method possibly generates fewer routes in total.

To use dynamic programming, the problem has to be divided into sequential stages ([Lundgren, Rönnqvist and Värbrand, 2012](#)). In the context of generating candidate routes for the SSP problem, a *stage* corresponds to a subset of partial routes of a given length. In each stage, there are several *states*, which correspond to a partial route. A state is described by a *label* and for each state, a subproblem is solved. The solution

of the subproblem gives an extension from the current stage to the next stage, where the next stage includes one more port visit.

Following Irnich (2008), the properties of a given state are represented by *resources* and when extending a label, the resources are updated with a *resource extension function*. Resources with regards to the SSP problem are for instance time, cost and required capacity on a ship. If an extension is feasible, meaning the resources do not exceed their allowed limits, a label is evaluated against all other labels in a given stage to check if the label is dominated, or if it dominates previously created labels. For a given label L_B to dominate another label L_A , denoted $L_B \prec L_A$, the three following dominance criteria must be fulfilled:

1. The labels have the same current node.
2. All feasible extensions of L_A are feasible for L_B .
3. Extending L_A to a new set of nodes never gives a better solution than extending L_B to the same set of nodes.

For a label to be able to dominate another when generating candidate routes, the same ports have to be included. Only when this is the case, the second general dominance criteria holds with certainty. Hence, it is implicitly understood that only labels with the same ports visited, irrespective of port visit sequence, and the same current port, potentially can be dominated.

7.1.2 Route Generation for the SSP Problem

The route generation procedure for the SSP problem is based on the assumptions presented in Chapter 5. A main assumption is that a daughter ship can meet a mother ship twice.

In order to let a daughter ship meet a mother ship twice, a mother ship has to visit ocean hubs on both the north-going and south-going part of its route. Therefore, a distinction is made whether an ocean hub can be visited by a north-going mother ship, denoted p^N or by a south-going mother ship, denoted p^S . When the main route includes coastal main ports, these can *only* be visited on the south-going part of the main route.

Further, to be able to synchronize daughter routes with a given main route, the duration on loop 1 and loop 2 for the daughter routes are calculated. The generation of daughter routes starts with loop 1 and once a south-going ocean hub is visited, the generation of loop 2 starts. The resulting duration of the loops are then compared to the time the mother ship uses between the same north-going and south-going ocean hub. The time it takes for the next mother ship to arrive in the north-going ocean hub is also calculated. If the duration on both loop 1 and 2 is shorter than the time the mother ship uses, the routes can be synchronized in the given ocean hub.

If an ocean hub is the northernmost point on a main route and hence only visited once a week, all daughter routes can be synchronized with this main route in the given ocean hub if the daughter route has a duration shorter than the maximum allowed duration.

7.2 Generating Main Routes

In this subsection, the generation of main routes is presented. Firstly, a description of the label data is presented. Then the label extension functions and the belonging stop conditions are described. Lastly, the pseudo codes for the algorithms used are presented.

Note that, due to the strict requirement of the port visiting sequence for main routes, no dominance occurs.

Label Data

The label data used for generating main routes are:

- n The current port visited.
- p The current path. This is a vector containing the current port visit sequence.
- c Total cost on a partial route including bunker cost, cargo handling costs and port costs.
- t Total current duration on a partial route when the ship is ready to leave the current port.
- b A vector with the departure times for the ports currently visited.
- u A binary value that takes the value 1 if a mother ship is sailing south and 0 if it is sailing north, relative to its last port visit.

The full label is written $L^M(n, [p], c, t, [b], u)$. The superscript M denotes that the label corresponds to a main route. For a given label, the current port visited is denoted $n(L)$. Similar notation is used to represent other properties of the label. As an example $t(L)$ is the total time spent on a partial route when a ship is ready to leave its current port.

The first and last port visit on a partial route is denoted s and e , respectively. For all main routes the start and end port correspond to the continental main port. The initial label can then be written: $L_0^M(s, [s], 0, 0, [0], 0)$.

Label Extensions

When a given label L_A is extended along the arc (i, j) from port $i = n(L_A)$ to port j , a new state is reached and new label L_B is created. The pseudo code for this is shown in Algorithm 3. The resources are updated with regards to properties of the arc and the new current port. This is done according to the following resource extension functions:

- Update Current Port

$$n(L_B^M) = j, \tag{7.1}$$

where j is the new current port.

- Extend Path

$$p(L_B) = [p(L_A), j] \tag{7.2}$$

The new current port is added to the path.

- Update Cost Mother

$$c(L_B^M) = \begin{cases} C^{TC} + C_{ij}^{OC}, & \text{if } i = s, \\ c(L_A^M) + C_{ij}^{OC}, & \text{if } t(L_B^M) \leq T^{1W} \text{ or } t(L_A^M) > T^{1W}, \\ c(L_A^M) + C^{TC} + C_{ij}^{OC}, & \text{if } t(L_A^M) \leq T^{1W} \text{ and } t(L_B^M) > T^{1W}, \end{cases} \quad (7.3)$$

where C^{TC} is the weekly time charter cost and C_{ij}^{OC} is the bunker cost of sailing from port i to port j in addition to the associated port costs in port j . The port costs include both a fixed port fee as well as a cost per container handled in the port. If the main route can be completed within one week, only one mother ship is needed. If more than one week is needed, a new mother ship has to be deployed in order to visit all ports weekly, and this incurs a new weekly time charter cost.

- Update Time Mother

$$t(L_B^M) = t(L_A^M) + T_{ij}^S + T_j^P, \quad (7.4)$$

where T_{ij}^S is the planned sailing time from port i to port j . The planned sailing time is estimated based on the design speed of the ships. However, if slack is added as a strategy to handle weather uncertainty, the sailing time on a leg is increased with a percentage, α . Then the expression for planned sailing time is $T_{ij}^S(1 + \alpha)$. T_j^P is the time spent in port j . The time spent in port j is a function of the amount of cargo loaded and unloaded, and the cargo handling rate.

The amount of cargoes handled by a mother ship in the continental main port and in coastal main ports if visited, is known with certainty when generating a main route. For these ports, the time spent on cargo handling, T_j^P , can be found exactly. The amount of cargo loaded and unloaded in each ocean hub is, however, *not* known with certainty until the daughter routes are generated and the master problem is solved. For each ocean hub visited on a main route an estimate is therefore used to calculate T_j^P . Since the total amount of cargoes handled in ocean hubs on a main route is known, the estimate is obtained by assuming that an equal amount of cargoes are handled in each ocean hub. This is in accordance with the example illustrated in Figure 5.2 in Section 5.4. Note that even though the estimate for a single ocean hub might be inaccurate, the total time needed for cargo handling in ocean hubs is accurate and hence the duration of the main route is exact.

- Extend Departure Times

$$b(L_B^M) = [b(L_A^M), t(L_B^M)] \quad (7.5)$$

The departure time for the current port in the label is added.

- Update Sailing North

$$u(L_B^M) = \begin{cases} 0 & \text{if } i = s, \\ 0 & \text{if NORTHPORT}(i, j) = j, \\ 1 & \text{if NORTHPORT}(i, j) = i, \end{cases} \quad (7.6)$$

where NORTHPORT(i, j) is a function determining whether port i or port j is the northernmost port among the two.

Label Extension Stop Conditions

The above-mentioned label extensions are only valid if the extended label L_B^M is resource feasible. If one of the following stop conditions are satisfied, the label is no longer extended. When a stop condition is met, the result can be either a fully generated route, or a partial route that is no longer resource feasible.

- Stop Destination Port

$$n(L_B) = e \tag{7.7}$$

If the current port is the destination port, the route is complete and the label should not be extended further.

- Stop Time Mother

$$t(L_B^M) > T^{2W} \tag{7.8}$$

The label is not extended further if the duration of a route is more than T^{2W} which is two weeks.

- The mother ship changes sailing direction from southwards to northwards after the northernmost port on the route is visited.
- A coastal main port is visited on the north-going part of the route.
- The northernmost port on the route is visited more than once.
- An ocean hub which is not the northernmost port on the route is only visited once.

Label-Setting Algorithm for Generating Main Routes

The algorithm for generating main routes is presented in Algorithm 2. The algorithm loops through all stages and extends all unfinished labels, L^{MU} , as well as adding all finished labels, L^{MF} , to the set of candidate routes, \mathcal{R}^M . The input to the algorithm is a set of ports, \mathcal{N} , that can be visited by a mother ship. $|\mathcal{N}|$ is the maximum number of port visits that is possible. \mathcal{G}_j contains all resource feasible labels with j number of port visits.

The extension of a label L_A to L_B is shown in Algorithm 3. This algorithm takes a label L_A and stage j from as input arguments. All possible ports visits in \mathcal{N} are looped through and for each port that is not visited before, the label is extended to L_B if the extension is resource feasible. Whether the extension is resource feasible or not is determined by the label extension stop conditions.

Because there is no domination of any labels when generating main routes, algorithm 4 simply adds the feasible label to the next stage.

Algorithm 2 Generating main routes.

```

1: procedure GENERATEMAINROUTES(Ports that can be visited by a mother
   ship  $\mathcal{N}$ )
2:    $\mathcal{R}^M \leftarrow \emptyset$  ▷ Initialize set of main candidate routes as empty
3:    $L_0^M \leftarrow (s, [s], 0, [0], 0)$  ▷ Initial label
4:    $\mathcal{G}_1 \leftarrow L_0^M$  ▷ Add initial label to  $\mathcal{G}_1$ 
5:   for each stage  $j = 1 \dots |\mathcal{N}|$  do
6:     for all Unfinished labels  $L^{MU} \in \mathcal{G}_j$  do
7:       EXTEND( $L^{MU}$ , stage  $j$ , possible ports to visit  $\mathcal{N}$ )
8:     end for
9:     for all Finished labels  $L^{MF} \in \mathcal{G}_j$  do
10:       $\mathcal{R}^M \leftarrow \mathcal{R}^M \cup \{L^{MF}\}$ 
11:    end for
12:  end for
13: end procedure

```

Algorithm 3 Extending a label.

```

1: procedure EXTEND(label  $L_A$ , stage  $j$ , possible ports to visit  $\mathcal{N}$ )
2:   for all possible ports to visit  $k \in \mathcal{N}$  do
3:     if  $k \notin p(L_A)$  then
4:        $L_B \leftarrow$  the label created when  $L_A$  is extended from  $n(L_A)$  to  $k$ 
5:       if  $L_B$  is a feasible extension then
6:         ADDTOSTAGE( $L_B, j + 1$ )
7:       end if
8:     end if
9:   end for
10: end procedure

```

Algorithm 4 Adding a label to the next stage.

```

1: procedure ADDTOSTAGE(label  $L_B$ , stage  $j$ )
2:   for all labels  $L \in \mathcal{G}_j$  do
3:     if  $L \prec L_B$  then ▷  $L_B$  is dominated
4:       stop procedure
5:     else if  $L_B \prec L$  then ▷  $L_B$  dominates a label  $L$ 
6:        $\mathcal{G}_j \leftarrow \mathcal{G}_j \setminus \{L\}$ 
7:     end if
8:   end for
9:    $\mathcal{G}_j \leftarrow \mathcal{G}_j \cup \{L_B\}$ 
10: end procedure

```

7.3 Generating Daughter Routes

The generation of daughter routes is presented in this subsection. Firstly, the full label is presented. Then the resource extension functions, stop conditions and dominance criteria are shown.

Label Data

The label data used for the generation of daughter routes is the following:

- n The current port visited.
- p The current path. This is a vector containing the current port visit sequence.
- w A set containing all ports visited. As opposed to the current path p , the sequence of ports is not of importance since w is a set. The set is used to evaluate if two labels contain the same ports.
- o The previous port visited. It is used for checking if loop 2 is being generated.
- l Binary value which is 1 if the generation of the second loop has started.
- c Total cost on a partial route including bunker cost, cargo handling costs and port costs.
- t Total current duration on a partial route when the ship is ready to leave the current port.
- t_1 Total remaining time available to finish loop 1 when the ship is ready to leave the current port.
- t_2 Total remaining time available to finish loop 2 when the ship is ready to leave the current port. This is the difference between the maximum allowed duration of a route and the time spent on loop 1.
- d_1 Total duration for the first loop of the partial route.
- d_2 Total duration for the second loop of the partial route.
- q^P Total amount of cargoes picked up in coastal daughter and coastal main ports. This is the amount of cargoes a daughter ship brings to a south-going hub.
- q^N Total minimum capacity needed to serve the ports visited. Both cargoes picked up and delivered to ports are taken into account.

The complete label is written $L^D(n, [p], \{s\}, o, c, l, t, t_1, t_2, d_1, d_2, q^P, q^N)$. The superscript D denotes that the label corresponds to a daughter route. For all daughter routes the start port s is also the ending port e and is always set to be an ocean hub. The initial label can then be written $L_0^D(s, [s], s, \emptyset, 0, 0, 0, T^{1W}, T^{1W}, 0, 0, 0, 0)$, where T^{1W} gives the numbers of hours in a week.

Label Extension Functions

The extension functions Update Current Port (7.1) and Extend Path (7.2) are also valid for generating daughter routes. The extension functions Update Cost Mother (7.3) and Update Time Mother (7.4) are modified and written below together with the additional extension functions needed for the generation of daughter routes.

- Extend Set of Visited Ports

$$w(L_B) \leftarrow w(L_A) \cup \{j\} \quad (7.9)$$

The new current port is added to the set of already visited ports.

- Update Cost Daughter

$$c(L_B) = c(L_A) + C_{ij}^{OC}, \quad (7.10)$$

where C_{ij}^{OC} is the operating cost that incurs when sailing from port i to port j as well as visiting port j . The cost of sailing from i to j is the bunker cost while the cost in port j includes both a fixed port fee and a cost per container handled. Note that no time charter cost is included. This cost is added in the master problem.

- Update Generating Loop 2

$$l(L_B) = \begin{cases} 1 & \text{if } o(L_A) = p^S \text{ or } l(L_A) = 1, \\ 0 & \text{otherwise.} \end{cases} \quad (7.11)$$

The generation of loop 2 has started if the last visited port was the south going ocean hub. Once loop 1 has started, the value of $o(L_B)$ cannot be set to 0.

- Update Time daughter

$$t(L_B) = t(L_A) + T_{ij}^S + T_j^P, \quad (7.12)$$

where T_{ij}^S is the planned sailing time from i to j as well as the sailing time from j to the destination ocean hub e . Similarly to the extension function Update Time Mother (7.4), the planned sailing time can include added slack.

The sailing time back to the ocean hub is included to more effectively determine if a route is feasible or not. If a ship exceeds the maximum duration T^{1W} on the way back to the ocean hub from the new current port, the route should be discarded immediately instead of extending it to the next stage.

T_j^P is the time spent on cargo handling in port j . In contrast to the generation of main routes, the time spent in both coastal ports and ocean hubs is known exactly for daughter ship routes.

- Update Time Available on Loop 1

$$t_1(L_B) = \begin{cases} t_1(L_A) - T_{ij}^S - T_j^P & \text{if } l(L_A) = 0, \\ t_1(L_A) & \text{if } l(L_A) = 1. \end{cases} \quad (7.13)$$

The time available to perform loop 1 is reduced with the sailing time T_{ij}^S and time in port T_j^P when loop 1 is currently being generated. If loop 2 is being generated, loop 1 is fully generated and t_1 is not updated.

- Update Time Available Loop 2

$$t_2(L_B) = t_2(L_A) - T_{ij}^S - T_j^P \quad (7.14)$$

The time available to perform loop 2 is reduced with the sailing time T_{ij}^S and time in port T_j^P when both loop 1 and loop 2 is being generated. The generation of loop 1 shortens the maximum available time to perform loop 2 and the generation of loop 2 shortens the time available on loop 2.

- Update Duration Loop 1

$$d_1(L_B) = \begin{cases} d_1(L_A) + T_{ij}^S + T_j^P & \text{if } l(L_A) = 0, \\ d_1(L_A) & \text{if } l(L_A) = 1, \end{cases} \quad (7.15)$$

The duration of loop 1 is increased with the sailing time T_{ij} and time in port T_j when loop 1 is currently being generated. If loop 2 is being generated, loop 1 is fully generated and d_1 is not updated.

- Update Duration Loop 2

$$d_2(L_B) = \begin{cases} d_2(L_A) + T_{ij}^S + T_j^P & \text{if } l(L_A) = 1, \\ d_2(L_A) & \text{if } l(L_A) = 0, \end{cases} \quad (7.16)$$

The duration of loop 2 is increased with the sailing time T_{ij} and time in port T_j when loop 2 is being generated. If loop 1 is being generated, the generation of loop 2 has not started yet and hence, the label is not updated.

- Update Last Port Visited

$$o(L_B) = n(L_A) \quad (7.17)$$

The last visited port in L_B is the current port in L_A .

- Update Capacity Required for Pick Up

$$q^P(L_B) = \begin{cases} q^P(L_A) + P_j & \text{if } l(L_B) = 0, \\ q^P(L_A) & \text{if } l(L_B) = 1, \end{cases} \quad (7.18)$$

P_j denotes to amount of cargoes picked up in port j . Note that the number of cargoes picked up on a route is only updated if loop 1 is being generated. As shown in the following extension function (7.19), q^P is not needed to calculate the ship capacity needed if loop 2 is being generated. Hence, it is not updated.

- Update Capacity Required for Pick Up and Delivery

$$q^N(L_B) = \begin{cases} \max \{q^P(L_B), q^N(L_A) + D_j\} & \text{if } l(L_B) = 0, \\ q^N(L_A) + P_j + D_j & \text{if } l(L_B) = 1 \end{cases} \quad (7.19)$$

$q^P(L_B)$ is defined as in the extension function Update Capacity Required for Pick-Up (7.18). Cargoes delivered to and picked up from port j is denoted D_j and P_j , respectively.

To better understand the extension function, the explanation is divided in two. First, the situation where an ocean hub is the northernmost point on the main route and only visited once is explained. Then, the situation where a daughter ship meets the mother ship twice is considered. Note that for both conditions, the formula gives the minimum capacity required when extending the partial route to a new port j . It is therefore not the amount of cargoes on the ship when it arrives in port j that is given by $q^N(L_B)$, but the capacity needed on the daughter ship when port j is included on the partial route.

Example 1: One Meeting Between a Mother and Daughter Ship

In this explanation, a loop 1 is being generated, and hence only the first condition in the extension function is considered. There is only one meeting between the mother and daughter ship and both loading and unloading the daughter ship is possible in this meeting.

By taking the maximum of the capacity required for pick up and the capacity required for both pick up and delivery, the minimum capacity required for the ship at any point on the route up until port j is accounted for. In other words, q^N is the maximum number of cargoes on the ship at any point from the beginning of the route, up until port j . Note that the amount of cargoes on a ship at any given time is the amount of cargoes picked up earlier on the route and the amount of cargoes that will be delivered to the ports later on the route. Because both cargoes picked up and delivered are accounted for, it can be beneficial to deliver a big load of cargoes early on the route to get free capacity to pick up cargoes later. This property makes the minimum capacity required for a given route dependent on the order in which the ports are visited. An example of this is shown in Figure 7.1

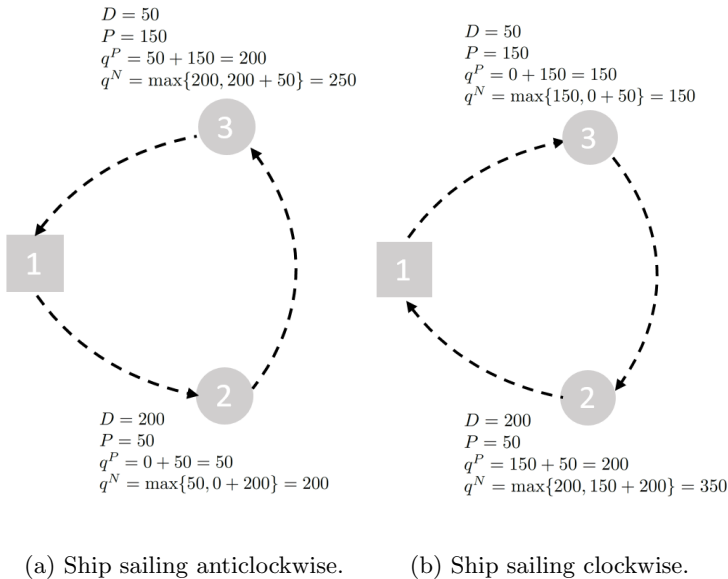


Figure 7.1: The sequence in which the ports are visited makes a difference for the capacity required.

For both Figure 7.1a and 7.1b, one ocean hub and two coastal daughter ports are visited. The total number of cargoes to be handled on the two routes is therefore the same. Recall that the calculated q^N in a given port j is the required capacity to serve all ports on the partial route, including port j . As an example when calculating q^N for port 2 in Figure 7.1a, this is the minimum capacity required for a ship serving the ocean hub 1 and port 2.

In Figure 7.1a, the daughter ship sails counterclockwise. The calculation of the minimum capacity is shown for each port as the partial route is extended. The minimum capacity required to serve the ocean hub and ports 2 and 3, sailing counterclockwise is 250. The point on the route where the ship is loaded with 250 cargoes is right after the visit in the ocean hub where it carries all cargoes that will be delivered on the route.

In Figure 7.1b, the daughter ship sails clockwise. The way to calculate q^P and q^N is the same as for Figure 7.1a, but the sequence of port visits has changed. Now, the minimum capacity required to serve the ocean hub and ports 3 and 2, sailing clockwise is 350. The point on the route where the ship is loaded with this amount of cargoes is between ports 3 and 2, where it carries the cargoes picked up from port 3 and those that is going to be delivered to port 2.

Example 2: Two Meetings Between a Mother and Daughter Ship

In this explanation, a route consisting of both loop 1 and 2 is considered. It is emphasized that when extending a label to include a new port, it is not known how many ports there are on the complete route until the label is fully extended. It is only known which ports are included so far on the partial route. This means that as long as a south-going ocean hub is not yet visited, a loop 1 is being generated and the capacity required for pick up and delivery is calculated as when there is only one meeting between a mother and daughter ship. Once a south-going ocean hub is visited, loop 2 begins and the calculation takes into account that there are two meetings between a mother and daughter ship.

Recall that cargoes can only be transshipped from a daughter ship to a mother ship in a south-going ocean hub and from a mother ship to a daughter ship in a north-going ocean hub. This property has an impact on the required cargo capacity for the daughter ship because the cargoes picked up on loop 2 have to be on the ship until the daughter ship is in a south-going ocean hub. Consequently, right after the visit in a north-going ocean hub in a given week, the daughter ship is loaded with the cargoes picked up from the ports on loop 2 the previous week in addition to all cargoes that will be delivered to the ports on the route in the given week.

Figure 7.2 shows how the minimum capacity required for pick up and delivery is calculated for a route consisting of both a loop 1 and 2. Again, note that even if the whole route is pictured, the calculation is based on how the minimum required capacity is updated when the partial route is extended. This means that q^N for a given port gives the capacity required for pick up and delivery on a partial route including all ports from ocean hub 1n to the given port. For ports 4 and 5 which are on loop 2, q^P is not calculated. This is because it is not needed to in the calculation of q^N .

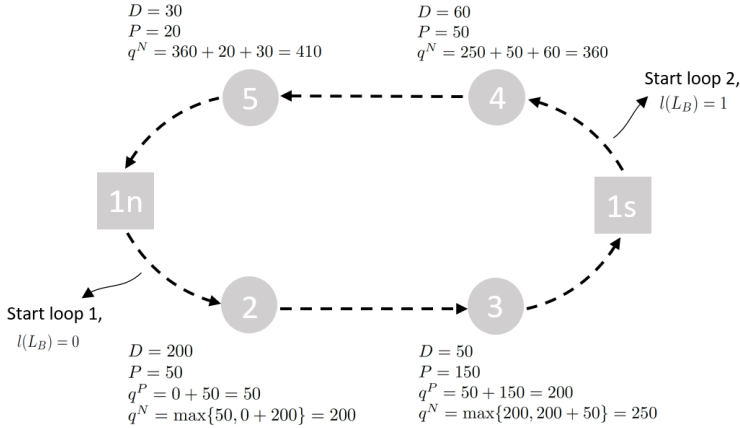


Figure 7.2: Minimum capacity required when a daughter ship visits ports both on loop 1 and 2.

When extending the partial route from ocean hub 1n to port 2 and port 2 to port 3, the minimum required capacity for pick up and delivery is calculated in the same way as in the example illustrated in Figure 7.1. At this point, there is no loop 2 on the partial route and hence both transshipment of cargoes from the mother to the daughter and the daughter to the mother could be done in ocean hub 1n.

When extending the partial route to ocean hub 1s, the conditions for the required capacity changes. Now, the daughter ship can only deliver cargoes to a mother ship in ocean hub 1s and pick up cargoes from a mother ship in ocean hub 1n. All the cargoes picked up after the visit in ocean hub 1s have to stay on the daughter ship until the next arrival in ocean hub 1s. Hence q^N is calculated as q^N in the previous port plus both the cargo picked up in and delivered to the current port.

This calculation is shown when the partial route is extended to port 4 and later port 5. All cargoes picked up and delivered to these ports are added to the required capacity. This is because the cargo picked up from these ports are on the daughter ship when cargo is transhipped from the mother ship to the daughter ship in ocean hub 1n. The result is that the required capacity on a daughter ship sailing the route in Figure 7.2 is 410.

A daughter ship with this capacity would be fully loaded right after the visit in ocean hub 1n. Here, the daughter ship carries all cargoes that must be delivered to each of the ports in addition to the cargoes picked up from ports 4 and 5 the previous week. Note that there are a lot free capacity on the daughter ship when it visits ports 4 and 5. This is because it delivers cargoes to the mother ship in ocean hub 1s. It might seem profitable to handle more cargoes in these ports, however, as shown in the calculations, a higher capacity for the daughter ship would be needed.

Label Extension Stop Conditions

The label extension stop condition Stop Destination Port (7.7) used when generating main routes is also valid for the generation of daughter routes. The additional stop conditions needed for the generation of daughter routes are stated below:

- Stop Daughter Time

$$t(L_B) > T^{1W} \quad (7.20)$$

If the duration of a daughter route is longer than the maximum allowed time for a daughter route T^{1W} , the route is not further extended.

- Stop Required Capacity

$$q^N(L_B) \geq \bar{Q}, \quad (7.21)$$

\bar{Q} is the maximal capacity available among the daughter ships. If there exists no daughter ship with enough capacity, the label should not further extended. Because $q^N(L_B) \geq q^P(L_B)$ always holds, a stop condition for $q^P(L_B)$ is not necessary.

- Stop Previously Visited

$$j \in p(L_A^M) \quad (7.22)$$

If the new current port is an element in the path to the previous label, the port is previously visited and an extension is not feasible.

Label Domination

As opposed to the generation of main routes, label domination can be utilized in the generation of daughter routes. For daughter routes $L_B \prec L_A$ if and only if:

$$n(L_B) = n(L_A) \quad (7.23)$$

$$w(L_B) = w(L_A) \quad (7.24)$$

$$q^N(L_B) \leq q^N(L_A) \quad (7.25)$$

$$d_1(L_B) \leq d_1(L_A) \quad \text{if } l(L_A) = 0 \text{ and } l(L_B) = 0, \quad (7.26)$$

$$d_1(L_B) \leq d_1(L_A) \text{ and } d_2(L_B) \leq d_2(L_A) \quad \text{if } l(L_A) = 1 \text{ and } l(L_B) = 1 \quad (7.27)$$

Criterion (7.23) makes sure the current port visited is the same for both labels. Criterion (7.24) makes sure that the same ports are visited and thus the same amount of cargoes are handled. Criterion (7.25) ensures that L_B has a lower or equal minimal required capacity to serve the ports visited than L_A .

The dominance criteria for time is covered by dominance criteria (7.26) and (7.27). Criteria (7.26) handles the case in which loop 2 is not currently generated. If a loop 2 is generated this is handled by criteria (7.27). For label L_B to dominate label L_A if a loop 2 is generated for both labels, the duration of both loop 1 and 2 must be lower or equal for L_B than L_A . Note that total duration is *not* used as a dominance criteria due to the synchronization of daughter and main routes. Consider a situation in which the total duration of L_B is shorter than for L_A , but $d_1(L_B) > d_1(L_A)$. Even though

L_B has a lower total duration, L_A might still be favorable when daughter and main routes are synchronized. Thus, the duration on loop 1 and 2 cannot be aggregated in the dominance criteria for time.

Note that the expression for cost, c , is *not* included in the dominance criteria (7.23)-(7.27). This is because cost is interdependent with time. Since dominance criteria (7.24) requires that the same ports are visited for both labels, the port costs and cargo handling costs are the same. Thus, the only difference in cost between L_A and L_B is the bunker cost, which is proportional to sailing time.

Label-setting Algorithm

The algorithm for generating daughter routes is presented in Algorithm 2 and is similar to Algorithm 5 for generating main routes. The most important difference relates to the fact that a set of daughter routes R_p is created for every ocean hub port $p \in \mathcal{P}^{OH}$. The output of Algorithm 5 is all feasible and undominated candidate daughter routes.

The algorithm for extending a daughter route label is identical to Algorithm 3 presented in Section 7.2. If loop 1 is being generated the set of ports that can be visited N when the label is extended, includes the south-going ocean hub p^S and not the north-going ocean hub p^N . This is because the daughter ship always has to meet a south-going mother ship to complete loop 1. Once loop 1 is complete, the generation of loop 2 starts. Then, the south-going ocean hub is deleted from the set of possible extensions, while the north-going ocean hub is added to the set.

If an extension is resource feasible, Algorithm 4, checks for dominance and adds all resource feasible labels to the next stage.

Algorithm 5 Generate candidate daughter routes.

```

1: procedure GENERATEDAUGHTERROUTES (Set of ocean hubs  $\mathcal{P}^{OH}$ , Ports
    $\mathcal{N}$  that can be visited by a daughter ship)
2:   for all Ocean hubs  $p \in \mathcal{P}^{OH}$  do
3:      $R_p \leftarrow \emptyset$   $\triangleright$  Initialize set of candidate daughter routes for ocean hub  $p$ 
4:      $L_0 \leftarrow (s, [s], \{s\}, \emptyset, 0, 0, 0, T^{1W}, T^{1W}, 0, 0, 0, 0)$   $\triangleright$  Initial label
5:      $\mathcal{G}_1 \leftarrow L_0$   $\triangleright$  Add initial label to  $\mathcal{G}_1$ 
6:     for each stage  $j = 1 \dots |\mathcal{N}|$  do
7:       for all unfinished labels  $L^U \in \mathcal{G}_j$  do
8:         EXTEND ( $L^U$ )
9:       end for
10:      for all Finished labels  $L^F \in \mathcal{G}_j$  do
11:         $\mathcal{R}_p \leftarrow \mathcal{R}_p \cup \{L^F\}$ 
12:      end for
13:    end for
14:  end for
15: end procedure

```

7.4 Synchronizing Main and Daughter Routes

After all candidate main and daughter routes are generated, Algorithm 6 is used to synchronize a set of daughter routes with a given mother route.

The algorithm loops through all of the generated main routes and for each main route all daughter routes are looped through. For each ocean hub pair (corresponding south-going and north-going ocean hub) the time the daughter ship has available to sail loop 1, T_{mp}^1 , is calculated. This is calculated as the difference between the arrival time in the south-going and north-going ocean hub on a main route. $T_{mp}^1 = t_{p^S}^m - t_{p^N}^m$, where $m \in \mathcal{R}^M$ and p^S and p^N is the south-going and north-going ocean hub $p \in \mathcal{P}^{OH}$, respectively. The time the daughter ship has to sail loop 2 is one week (168 hours) less the time it has to sail loop 1. The available time on loop 2 is denoted $T_{mp}^2 = T^{1W} - T_{mp}^1$. If the ocean hub is the northernmost point on the main route and only visited once, the only requirement for a daughter route is that the duration is less than one week.

The output of Algorithm 6 is the set \mathcal{R}_{pm}^D . This is the set of daughter routes that includes port p and is synchronized with a given main route m .

Algorithm 6 Synchronize main and daughter routes.

```

1: procedure SYNCHRONIZEROUTES(Set of mother routes  $\mathcal{R}^M$ , set of daughter
   routes  $\mathcal{R}^D$ )
2:   for all  $m \in \mathcal{R}^M$  do
3:     for all  $d \in \mathcal{R}^D$  do
4:       for each ocean hub  $p$  on main route do
5:         if  $T_{mp}^1 \geq \text{duration loop 1}$  and  $T_{mp}^2 \geq \text{duration loop 2}$  then
6:            $\mathcal{R}_{pm}^D \leftarrow \mathcal{R}_{pm}^D \cup \{d\}$ 
7:         end if
8:       end for
9:     end for
10:  end for
11: end procedure

```

Chapter 8

Simulation Model

This chapter presents the simulation model used for evaluating how duration and synchronization violations affects solutions to the SSP system. To evaluate this, the speed of a ship is simulated based on simple ship specifications and significant wave height obtained from historical weather data. This use of historical weather data makes the simulation model dependent on the geographic positions of a ship as it sails along a route. To sum up, the simulation model offers a simplified way to obtain approximate, yet reasonable, realistic statistics on how a solution to the SSP problem performs in real world operations.

The simulation model is dynamic as it simulates how the speed of a ship varies along a route. Further, the simulation model can be categorized as a discrete event simulation model as the speed changes based on a sequence of discrete events in time. When an event occurs, the speed is updated and then treated as constant until the next event occurs. An event is defined to occur each time a ship has sailed a certain distance and when a ship departures at a port.

Section 8.1 describes how historical weather data for significant wave height are used as weather scenarios. An approximate method for determining sailing speed based on significant wave height and simple ship specifications is presented in Section 8.2. Section 8.3 covers how geographical information from sailing legs is utilized. Section 8.4 explains how duration and synchronization violations can be analyzed in order to incorporate the effects of weather delays. Finally, Section 8.5 summarizes the previous sections by describing the overall simulation methodology.

8.1 Weather Conditions

The scenarios used to simulate real world weather conditions are based on historical weather data for significant wave height. Significant wave height, denoted H_S , is defined as the average height of the highest one-third waves [DNV GL AS \(2014\)](#). Figure 8.1 illustrates this definition by showing a frequency distribution of wave heights.

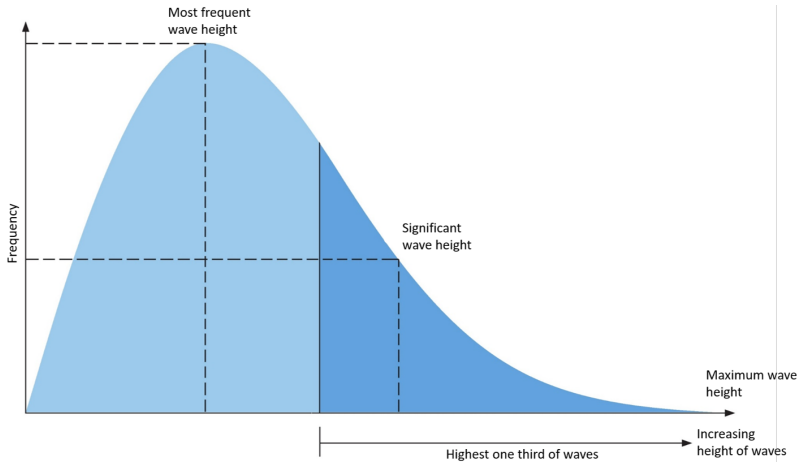


Figure 8.1: A frequency distribution of wave heights. The significant wave height is the average height of the highest one-third of the waves. Modified figure from [Australian Government - Bureau of Meteorology \(2015\)](#).

In maritime navigation, significant wave height is often used as an important parameter to describe the weather. Many other parameters, for instance related to wind and current are important as well. For the interested reader, a thorough summary of analytical expressions for many different weather parameters are found in [DNV GL AS \(2014\)](#). However, for simplicity, it is assumed that significant wave height is the only needed parameter to describe the weather in this simulation model. When wind speed is high, the significant wave height is probably also high, and such correlations can make the assumption reasonable.

8.2 Sailing Speed

Obtaining accurate sailing speed estimates based on ship specific parameters and weather conditions involves complex hydrodynamic relations which are beyond the scope of this Master's thesis. Furthermore, due to the conceptual nature of the SSP logistic system, it is impossible to obtain parameters that are accurate enough to make it worthwhile to use complex hydrodynamic relations. For this reason, this Master's thesis aims to find relations that are as simple as possible yet providing meaningful results.

Subsection [8.2.1](#) gives a brief introduction to some of the most fundamental formulas related to sailing speed. When simulating sailing speed, it is assumed that ships sail with constant power. This assumption is explained in Subsection [8.2.2](#). In Subsection [8.2.3](#), methods for calculating ship resistance are outlined. Lastly, in Subsection [8.2.4](#), a final expression for sailing speed dependent upon significant wave height and simple ship geometry is given.

8.2.1 Brief Introduction to Fundamentals of Ship Propulsion

For literature focusing on the fundamentals of ship propulsion the reader is referred to [Bertram \(2012\)](#), [Kristensen and Lützen \(2012\)](#) and [MAN Diesel & Turbo \(2011\)](#).

The fundamental relation between speed, power and resistance, commonly occurring in physics in general, is also applicable for ships sailing at sea. The relation is given as follows:

$$P_E = V \cdot R_{tot}, \quad (8.1)$$

Within the setting of ship propulsion, P_E denotes the propulsion power needed to move a ship through water at speed V . This power can also be referred to as the effective towing power since it gives the power needed to tow a ship without any propulsive system. R_{tot} denotes the total resistance of a ship which is the total force that works in the opposite direction of the movement of a ship.

It is worth noting that the power delivered by a ship's engine, often referred to as "brake power", P_B , is higher than P_E due to various inefficiencies related to the propeller, shafts and bearings. Thus $P_E = \eta_T \cdot P_B$, where $\eta_T < 1$ gives total efficiency.

The total resistance, R_{tot} , can be decomposed as follows:

$$R_{tot} = R_{CW} + R_{AW} + R_{AA} \quad (8.2)$$

R_{CW} is the calm water resistance. It gives the resistance of a ship sailing in calm water. This resistance is mainly caused by friction between the ship's hull and the water, waves generated by the ship moving through water and the creation of turbulence. R_{CW} varies with speed and especially at lower speeds, the frictional resistance gives the greatest contribution to the calm water resistance ([MAN Diesel & Turbo, 2011](#)).

When a ship sails in rougher conditions than calm water, the total resistance increases. R_{AW} gives the added resistance due to waves. In this regard, this refers to waves in the sea external to a ship, i.e. waves not generated by a ship itself. R_{AA} gives the added resistance due to wind.

According to [MAN Diesel & Turbo \(2011\)](#) the resistance due to waves and wind typically accounts for about 20-30% of the total resistance. These values are however only a rough estimate. When sailing in head on sea, the increase in resistance can approximately be as much as 50-100%.

8.2.2 Using a Constant Power Approach

When simulating ship speed, it is assumed that ships sail with constant power. Rearranging equation (8.1) speed can be expressed as $V = P_E/R_{tot}$. Accordingly, if the total resistance increases, for instance due to increasing environmental loads such as increasing significant wave height, the speed will decrease. Since the power is at a constant level, the fuel consumption is also constant.

In Chapter 5, a speed-up policy was introduced as a recovery action to mitigate disruptions. If conditions allow for a speed-up, the power can be raised by a certain

percentage, limited by the maximum power output. Consequently, there are two possible constant power values. The power used for the speed-up policy is referred to as *speed-up power* while the power normally used is referred to as *design power*. Use of the speed-up power can be regarded as a special case, and the power should therefore not fluctuate frequently between the two power values.

The realism of the constant power assumption originates from the fact that ships are often designed to be operated at a certain power for which the engines run efficiently. This does not, on the other hand, imply that ships always sail at constant power in reality, but it is a simplification made in this Master's thesis. An alternative approach could be to assume ships sailing at a constant speed regardless of environmental loads. [Kjølleberg \(2015\)](#) tests this approach in a simulation model for supply ships at the Norwegian west coast. He concludes that it seems to be a bad approximation due to a resulting unrealistically high fuel consumption rate. Another more advanced approach is to allow for constant speed as long as it is realistic in terms of, for instance, speed limits and weather conditions. However, such an approach requires detailed operational information and is beyond the scope of this Master's thesis.

8.2.3 Calculating Total Resistance

In the following, it is explained how sailing speed and significant wave height is related. The formulas presented form a basis for the speed calculations in the simulation model.

Calm Water Resistance (R_{CW})

To find R_{CW} , equation (8.1) is solved for $R_F = R_{tot}$ with a constant power P_E and design speed V . The needed power at design speed is provided as input data.

Even though R_{CW} varies with speed, it has been treated as a constant value in the simulation model. In general, this is a rough approximation, but given the need to avoid complexity in calculations due to limited input data, letting R_{CW} vary with speed would probably not increase the realism of the model significantly compared to the increase in complexity.

With a constant calm water resistance, more power than realistic is needed at speeds lower than the design speed in order to overcome the calm water resistance. Thus this assumption contributes to underestimate the speed in the simulation model. At speed higher than design speed, the effect works the opposite way and the speed is overestimated.

Added Resistance due to Waves (R_{AW})

Finding an expression for R_{AW} based on significant wave height is challenging. Obtaining relations between significant wave height and ship speed become mathematically complex and require accurate information about specific ship parameters.

[Van den Boom, van der Hout and Flikkema \(2008\)](#) compare several existing methods for calculating added resistance due to waves during speed trials of ships. A speed trial is an actual test of a ship and often performed to validate contractual specifications. Speed trials should ideally be performed in calm water, but in practice, the sea state could be low to mild during a test. To correct for deviations, several correction methods exist. [Van den Boom et al. \(2008\)](#) conclude that existing wave correcting methods are

unreliable and propose two new methods named STAwave-1 and STAwave-2. These methods are recommended as a standard by ITTC (2014).

STAwave-1 is the simplest of the two methods and is based on the fact that for today's large ships the head waves encountered in trial conditions are normally short compared to ship length and speed (Van den Boom et al., 2008). The method estimates the resistance increase in head waves provided that a ship does not heave and pitch (ITTC, 2014). The formula of the method is given as,

$$R_{AW} = \frac{1}{16} \rho g H_s^2 B \sqrt{\frac{B}{L_{BWL}}}, \quad (8.3)$$

where R_{AW} gives the added resistance in waves and g is the gravity constant. The significant wave height is denoted H_s . The beam of the ship is B and L_{BWL} is the length from the bow on the water line to 95% of maximum beam. In order to find L_{BWL} , it has been estimated that L_{BWL} is 10% of the total length of a ship.

The formula is extensively validated for significant waves heights satisfying the following condition: $H_S \leq 2.25 \sqrt{L_{pp}/100}$, where L_{pp} gives the ship length between the perpendiculars, which is bit less than the overall length of a ship.

The assumptions needed for the method will not always be fulfilled in the simulation model. Ships in the simulation model will for instance encounter waves in which the vessel is heaving and pitching. Further, the simulation model will treat all waves as head waves. Lastly, the above-stated condition for the height of the significant wave height will be violated. However, the formula is easy to use and with few input data given in the SSP system, this formula can serve as a proxy for relating speed and significant wave height. For this reason, the formula has been applied in the simulation framework.

Wind Resistance (R_{AA})

As a simplification, wind resistance has not been considered in the simulation model. Wind resistance will become significant for high wind speeds, but it is assumed this effect will be reflected by the wave resistance.

8.2.4 The Final Expression for Sailing Speed

Based on the previous subsections the final expression for speed becomes:

$$V = \frac{P}{R_F + R_{AW}} = \frac{P}{R_F + \frac{1}{16} \rho g H_s^2 B \sqrt{\frac{B}{L_{BWL}}}}, \quad (8.4)$$

where P , the constant power, is found based on typical power values provided in statistics for container ships as described in Chapter 9. R_F is treated as a constant value obtained as described in Subsection 8.2.3. R_{AW} is found in equation (8.3).

Based on the data collected in Chapter 9, Figure 8.2 shows how the speed decreases as a function of increasing significant wave height. The figure shows the sailing speed with the design power and with the speed-up power.

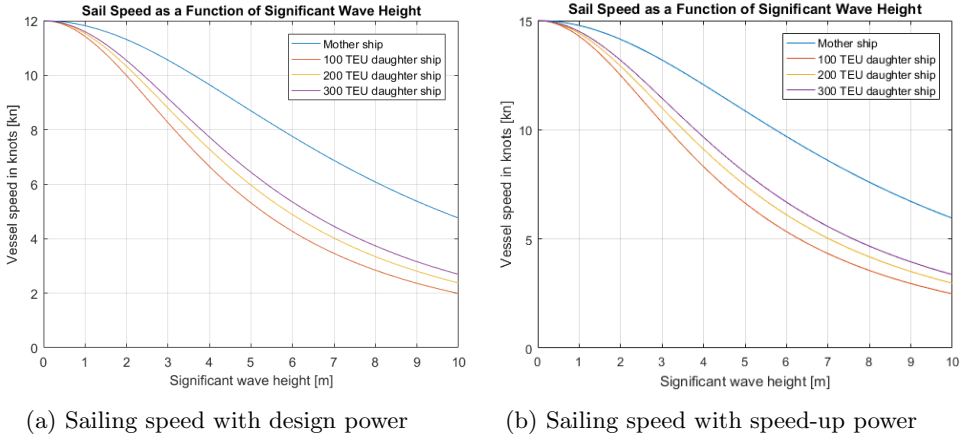


Figure 8.2: Speed plot showing how the speed decreases as a function of increasing significant wave height.

8.3 Sailing Legs with Geographical Information

In order to calculate sailing speed based on historical weather data, it is necessary to know the geographic position of a ship as it sails along a route. This requires detailed information about the sailing legs on a route, which defines how a ship navigates when sailing between a pair of ports. A sailing leg corresponds to an arc in a graph network.

Each point on sailing leg at which the direction of a ship is changed is referred to as a *waypoint*. The line between two consecutive waypoints is referred to as a *sub leg*.

The speed of a ship is set to be updated every time the ship has sailed a certain distance, hereafter referred to as a *step distance*. The speed is also updated at the departure port of a sailing leg. The point at which the speed is updated is referred to as an *observation point*.

The historical weather scenarios contain gridded data on significant wave height. This means that weather data is only accessible at certain locations, which hereafter are referred to as *data points*. At each observation point the significant wave height is found by locating the closest data point.

Figure 8.3 illustrates a sailing leg. As seen in the figure, the direction of a ship changes at each waypoint. The observation points are equally separated by the step distance which in the figure is set to be five nautical miles. In the background of the figure, the gridded data points are shown.

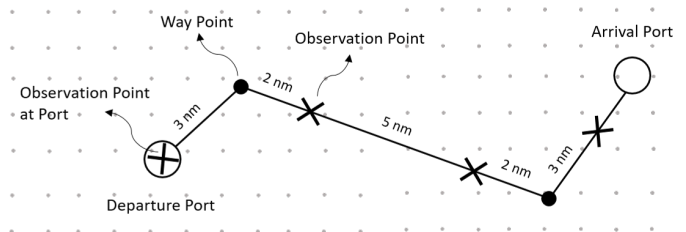


Figure 8.3: Illustration of a sailing leg. The ship changes direction at the waypoints and the speed is updated at every observation point.

8.3.1 Geometrical Calculations

The location of all points in Figure 8.3 can be represented with latitude and longitude coordinates. This makes it possible to calculate distances and directions between them. This has been done by using a spherical coordinate system to represent the surface of the earth. For short distances, the surface of the earth could be assumed to be flat, but for longer distances, such as between Maasvlakte and Orkanger port, this is not the case. By using a spherical coordinate system, the simulation model becomes more generic.

By calculating the distance between the waypoints on a sailing leg, the total distance can be found. This makes it possible to create a distance matrix for all sailing legs. Distance calculations are also needed to search for the closest data point to a given observation point. In order to find the locations of the observation points, the direction between waypoints must be known.

In the following, formulas used to calculate directions and distances are presented. The formulas are obtained from [Chris \(2017\)](#).

Distance between Two Points

The distance between two points has been found by computing the great-circle distance using the haversine formula. The great circle distance is the shortest distance between two points, measured along the surface of the sphere. The haversine formula is given as follows:

$$\begin{aligned}
 a &= \sin^2(\Delta\phi/2) + \cos\phi_1 \cdot \cos\phi_2 \cdot \sin^2(\Delta\lambda/2), \\
 c &= 2 \cdot \arctan2(\sqrt{a}, \sqrt{1-a}), \\
 l &= R \cdot c,
 \end{aligned} \tag{8.5}$$

where $\Delta\phi$ and $\Delta\lambda$ is the difference in latitude and longitude, respectively, between two points (ϕ_1, λ_1) and (ϕ_2, λ_2) . R is the radius of the earth. l is the distance between the two points. All angles must be given in radians.

Direction between Two Points

The direction a ship must sail to get from one line point to another, following the great circle path, is often referred to as forward azimuth. The forward azimuth between two points is given as follows:

$$\theta = \arctan2(\sin \Delta\lambda \cdot \cos \phi_2, \cos \phi_1 \cdot \sin \phi_2 - \sin \phi_1 \cdot \cos \phi_2 \cdot \cos \Delta\lambda), \quad (8.6)$$

where θ gives the forward azimuth, (ϕ_1, λ_1) is the start point and (ϕ_2, λ_2) is the ending point. $\Delta\lambda$ is then the difference in longitude. All angles must be given in radians.

Destination Point given Distance, Direction and Start Point

Given a start point, and a direction and distance to sail, the destination point can be calculated. A formula which finds the ending point given a starting point with the forward azimuth and a distance traveled can be used in this context. The formula is given as follows:

$$\begin{aligned} \phi_2 &= \arcsin(\sin \phi_1 \cdot \cos \delta + \cos \phi_1 \cdot \sin \delta \cdot \cos \theta), \\ \lambda_2 &= \lambda_1 + \arctan2(\sin \theta \cdot \sin \delta \cdot \cos \phi_1, \cos \delta - \sin \phi_1 \cdot \sin \phi_2), \end{aligned} \quad (8.7)$$

where (ϕ_1, λ_1) is the start point and (ϕ_2, λ_2) is the end point. θ gives the forward azimuth at the starting point. δ is the angular distance d/R where d is the step distance and R is the radius of the earth.

8.4 Incorporating Weather Delays

As emphasized in Chapter 3, synchronization and duration violations impact the SSP logistics system. To get a better understanding of how violations occur and their impact, a more detailed discussion is carried out in this section. Subsection 8.4.1 explains the mathematical relationship between the synchronization and duration violations, while insight into how a delay occurring in a given week affects the following weeks is given in Subsection 8.4.2. Lastly, subsection 8.4.3 illustrates how idle time can protect against duration violations.

8.4.1 Calculating Synchronization and Duration Violations

This subsection provides mathematical expressions for synchronization and duration violations. Recall that a loop 1 is the part of the daughter route between the north and south-going ocean hub and a loop 2 is between the south and north-going ocean hub. If the daughter ship only meets a mother ship once a week, this is also referred to as a loop 1. Synchronization violations can happen on both loops and they can affect each other. Even though the conditions for a violation on each loop are similar, a distinction is made for clarity.

Synchronization Violations on Loop 1

A synchronization violation on loop 1 happens in a south-going ocean hub and is caused by one of two following events:

1. A daughter ship is more delayed on loop 1 than its planned idle time, such that the mother ship has to wait.
2. A mother ship uses longer time than estimated between the north and south-going ocean hub such that the daughter ship must stay idle longer than planned.

Summarized, there is a synchronization violation on loop 1 if one of the following two conditions are satisfied:

- Daughter ship causes synchronization violation on loop 1

$$\max(D_{p^N p^S}^D - I_{L1}^D, 0) > D_{p^N p^S}^M, \quad (8.8)$$

The delay between the north-going and south-going ocean hub p for a daughter and mother ship respectively is denoted $D_{p^N p^S}^D$ and $D_{p^N p^S}^M$, respectively. The planned idle time for the daughter ship before the synchronization with the mother ship at the end of loop 1 is denoted I_{L1}^D . If the expression inside the parenthesis is greater than zero, it means that the delay on the daughter route on loop 1 is larger than the planned idle time. Note that the delay is defined as duration longer than planned, not including planned idle time.

If the delay, after the planned idle time is utilized for sailing, is larger than the delay for the mother ship between the north and south-going ocean hub, it means that the mother ship has to wait for the daughter ship and a synchronization violation on loop 1 occurs.

- Mother ship causes synchronization violation on loop 1

$$D_{p^N p^S}^M > D_{p^N p^S}^D, \quad (8.9)$$

If the delay on the mother route between the north and south-going ocean hub is larger than the delay on the daughter route between the same ports, it means the daughter ship must stay idle longer than planned time and hence a synchronization violation occurs.

Synchronization Violations on Loop 2

A synchronization violation on loop 2 happens in a north-going ocean hub if the mother and daughter ship are not able to meet each other without increasing the idle time for either of the ships. This might happen in one of the following two ways:

1. The daughter ship is more delayed on its loop 2 than its planned idle time before the synchronization with the mother ship in a north-going ocean hub
2. A mother ship is delayed on its way from the continental main port to the north-going ocean hub such that the daughter ship must stay idle longer than planned

Since loop 1 has to be performed before loop 2, it means that a delay on loop 1 might cause a delay on loop 2. Initially, a daughter ship has one week available to complete a route and after loop 1 is done, there is one week less the duration on loop 1 available to complete loop 2 and synchronize with the north-going mother ship. Accordingly, a delay for either the mother or the daughter ship on loop 1 affects the daughter ship on loop 2.

Similarly to a synchronization violation on loop 1, there are two ways a synchronization violation on loop 2 can occur:

- Daughter ship causes synchronization violation on loop 2

$$\max(D_{p^s p^N}^D - I_{L2}^D, 0) > D_{CMp^N}^M, \quad (8.10)$$

$D_{p^s p^N}^D$ denotes the delay on the daughter route between the south and north-going ocean hub visit, i.e. the delay on loop 2. Note that a delay causing a late synchronization on loop 1 is included in the expression for delay on loop 2. I_{L2}^D denotes the planned idle time on loop 2, before the synchronization with the north-going mother ship. $D_{CMp^N}^M$ is the total delay for the mother ship between the continental main port and the north-going ocean hub, including both weather delays and delays due to synchronization violations. Similarly to the synchronization violation on loop 1 caused by a daughter ship (8.8), the expression in the parenthesis is greater than zero if the delay is longer than the planned idle time. If a delay is less than the planned idle time, idle time is used as a buffer and the daughter ship is ready for the synchronization when the mother ship arrives.

- Mother ship causes synchronization violation on loop 2

$$D_{CMp^N}^M > D_{p^s p^N}^D, \quad (8.11)$$

where $D_{p^s p^N}^D$ denotes the delay on the daughter route between the south and north-going ocean hub visit, i.e. the delay on loop 2. $D_{CMp^N}^M$ is the delay for the mother ship between the continental main port and the north-going ocean hub. If the delay on the mother route is larger than the delay for the daughter route, the daughter ship has to stay idle longer than expected before the synchronization and there is a synchronization violation.

Note that after a daughter ship has completed one round trip, a synchronization violation on loop 2 can cause implications for loop 1 on the next round trip. This effect is captured by accounting for duration violations as outlined in the following.

Duration Violations in the SSP Logistics System

A duration violation is always a result of a delay caused by harsh weather conditions and a specific route is affected. However, analyzing duration violations cannot be done by looking only at the individual routes. This is because delays that occur due to harsh weather on a given route might affect other routes through the synchronizations.

Equations for duration violations on a mother route (8.12) and duration violation on a daughter route (8.13) show how synchronization violations might amplify a delay caused by harsh weather conditions.

- Duration violation on main route

$$PD^M + D^M + \sum_{p \in \mathcal{P}^{OH}} D_p^{SYNC^D} > T^{2W}, \quad (8.12)$$

where PD^M is the planned duration for the main route. The planned duration is *not* included planned idle time. Total delay on the main route due to *only* sailing with reduced speed is denoted D^M . The summation term is the magnitude of all the synchronization violations caused by waiting for daughter ships in ocean hubs. T^{2W} denotes the maximum allowed duration for a main route, which is two weeks when two mother ships are deployed.

- Duration violation on daughter route

$$PD_{p^N p^S}^D + \max(D_{p^N p^S}^D, I_{L1}^D) + D_{p^S}^{SYNC^M} + PD_{p^S p^N}^D + \max(D_{p^S p^N}^D, I_{L2}^D) + D_{p^N}^{SYNC^M} > T^{1W}, \quad (8.13)$$

The first three terms describe the total time to complete loop 1. The planned duration of loop 1, *only* including sailing and cargo handling time, is denoted $PD_{p^N p^S}^D$. The time from the end of the planned duration to a mother ship is supposed to arrive is the maximum of the delay on loop 1 due to harsh weather conditions, $D_{p^N p^S}^D$ and the planned idle time before the synchronization in the south-going ocean hub, I_{L1}^D . The final term included in the actual total time to complete loop 1 for the daughter ship is $D_{p^S}^{SYNC^M}$. This denotes additional time a daughter ship has to wait to synchronize with the mother ship. Note that the time, $D_{p^S}^{SYNC^M}$, is *not* included in the two previous terms in the inequality.

The three last terms represent similar notation, but it is valid for loop 2.

To better understand how a duration violation for a daughter route is calculated, consider the small example, calculating total time to complete loop 1:

On loop 1, the daughter ship is expected to use 50 hours on sailing and cargo handling time. This is the planned duration. Further, the daughter ship is five hours delayed because of harsh weather. The five hour delay is compared to the planned duration. The planned idle time before the south-going ocean hub visit is ten hours. This is the planned idle time found in the route generation procedure, not taking any delays into account. Because of this, the max condition, $\max(D_{p^N p^S}^D, I_{L1}^D)$ gives 10 hours. The total duration of loop 1 when the daughter ship is ready to synchronize, is 60 hours. If the mother ship is not ready for the synchronization at that time, the extra delay caused by synchronization violation from the mother ship is accounted for by $D_{p^S}^{SYNC^M}$. For example, if the mother ship is 10 hours delayed, the total time to complete loop 1 for the daughter ship is 70 hours.

8.4.2 Impact of Delays Over Multiple Weeks

When determining how to penalize duration violations, it is important to consider how a delay in one week affects the system in following weeks.

In practice, a ship with a duration violation in a given week is not able to start sailing its route the next week as planned. Consider a situation where the duration of a route is five hours longer than the maximum allowed duration. This means the ship sailing the route the next week has to start five hours after schedule. When this happens, not all ports are visited on a weekly basis.

Consider that a ship sailing a given route violates its maximum allowed duration by five hours every week. This means the delay for the ship increases with five hours each week and after 20 weeks, the arrival in a port is 100 hours after the initially scheduled arrival.

Consequently, the delay in a given week can have a potentially huge impact on the routes sailed in following weeks. Figure 8.4 illustrates this concept, where a duration violation in week t is transferred to week $t + 1$. T denotes the total number of weeks in the simulation period.

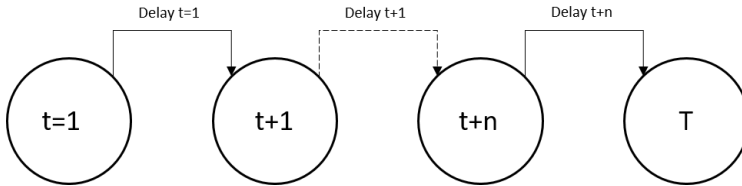


Figure 8.4: A duration violation in a given week has impact on the next week

It should be noted that from a shipping company's perspective, a system incurring duration violations that propagate in many of the weeks is not viable. Hence, a route composition giving these results would not be implemented without making changes to it. However, by letting the duration violations propagate from a given week to the next, route compositions that are often incurring duration violations are receiving a high penalty cost and are less likely to be chosen as a final solution in the optimization-simulation framework.

8.4.3 Utilize Idle Time to Protect Against Violations

The small example in Subsection 8.4.2 illustrates how a delay can have huge consequences for later time periods. However, planned idle time on a route can be utilized to avoid the propagating effect. Similarly to how an airline route recovers at night because there are no scheduled flights that time, a ship can recover from a delay without incurring a duration violation by utilizing the idle time (Brouer et al., 2013). This is shown in Figure 8.5.

The black line within the curly bracket for each week is the maximum allowed duration for a route. The red part of the line symbolizes duration of a route longer than the

maximum allowed duration and is a duration violation. This duration violation is transferred to the next simulated week as an initial delay.

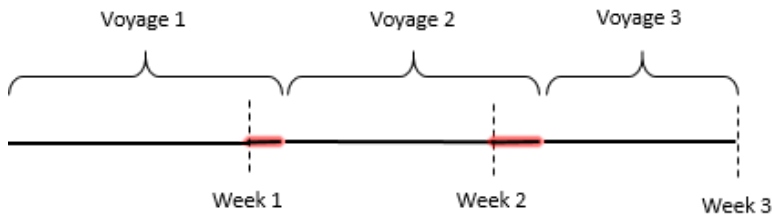


Figure 8.5: A duration violation in a given weeks becomes initial delay the next week. Planned idle time works as a buffer to protect from propagating duration violations.

In the first week, there is a duration violation, symbolized by the red line segment on the right side of week 1. Clearly, the voyage starting in week 1 is not completed until the beginning of week 2.

The voyage in week 2 cannot start until the voyage that started in week 1 is completed. Hence, it is initially delayed. In week 2 even more delays occur and the voyage will be even more delayed than its initial delay. Thus, the duration violation magnitude increases as can be seen since the red line segment increases.

In week 3, the voyage is initially delayed, but it is completed exactly in the end of week 3. No duration violation are incurred this week, despite the initial delay from the previous two weeks. The reason why the delay is mitigated is planned idle time. The route has a shorter duration than the maximum allowed duration and if there are no delays in a given week, an initial delay from previous weeks can be mitigated.

The example shows how planned idle time can be utilized in order to reset a system that has been disrupted because of duration violations. Both mother and daughter ships can utilize planned idle time this way. However, it is emphasized that a mother ship can never leave the continental main port before its planned departure. In all other ports and ocean hubs, the ships can leave as soon as they are ready. This means that if both a mother ship and daughter ship is ready to synchronize in an ocean hub, they can do so, even if it is before the expected time found in the route generation procedure.

8.5 The Simulation Process

The previous sections provide insight into theory needed for the simulation model. This section describes how the theory is combined to create the methodical framework used in the simulation model.

8.5.1 Pseudo Code for Simulating a Ship along a Sailing Leg

Algorithm 7 shows a pseudo code for simulating a ship along a sailing leg. The following data are needed as input:

- *WeatherData* - gives gridded data on significant wave height, H_S .
- *LegInfo* - sailing leg information giving the waypoints with corresponding distances and directions between them.
- *ShipType* - specifications for a given ship type. This includes information about design speed V and ship geometry needed for speed calculations.
- *DepartureTime* - Time of departure.
- *StepDist* - the step distance between each observation point.
- *MaxDist* - Maximum distance allowed between an observation point and a corresponding data point. If the maximum distance is violated H_S is set to zero. This is further explained below.

The output from the pseudo code is the time when the ship arrives in the destination port.

Algorithm 7 Pseudo code for simulating a ship along a sailing leg

```

1: procedure SIMULATESHIPALONGLEG(WeatherData, LegInfo, ShipType,
  DepartureTime, StepDist, MaxDist)
2:   Time  $\leftarrow$  DepartureTime
3:    $(\phi, \lambda) \leftarrow$  first waypoint ▷ This also gives first observation point
4:   IterationStep  $\leftarrow$  StepDist ▷ Distance to sail at each iteration
5:   Dist = 0 ▷ Distance sailed on sailing leg
6:    $H_S = \text{FINDWEATHER}((\phi, \lambda), \textit{Time}, \textit{WeatherData}, \textit{MaxDist})$ 
7:    $\textit{Speed} = \text{FINDSPEED}(H_S, \textit{ShipType})$ 
8:   for each sub leg do
9:     SubLegDist  $\leftarrow$  Distance from departure port to last waypoint on sub leg
10:    while Dist + IterationStep < SubLegDist do
11:      Time = Time + IterationStep/Speed
12:      Dist = Dist + IterationStep
13:       $(\phi, \lambda) = \text{FINDNEXTPOINT}((\phi, \lambda), \textit{IterationStep}, \textit{LegInfo})$ 
14:       $H_S = \text{FINDWEATHER}((\phi, \lambda), \textit{Time}, \textit{WeatherData}, \textit{MaxDist})$ 
15:       $\textit{Speed} = \text{FINDSPEED}(H_S, \textit{ShipType})$ 
16:      IterationStep = StepDist
17:    end while
18:    Time = Time + (SubLegDist - Dist)/Speed
19:    IterationStep = IterationStep - (SubLegDist - Dist)
20:    Dist = SubLegDist
21:  end for
22: end procedure

```

Algorithm 7 can briefly be explained as follows: First, the speed is found at the departure port. Then, for each consecutive waypoint pair, also referred to as a sub leg, the speed is updated if one or more observation points are located on the sub leg. Otherwise, no speed update is made. The algorithm stops when the last sub leg is checked.

The function `FINDWEATHER` finds the significant wave height. With a given observation point, the closest data grid point must be found. In addition, a search must be done to find the best match between the time when a ship reaches an observation point and the time the data value is valid for.

The distance to be minimized is calculated according to equation (8.5). Since all observation points and data grid points are predetermined, the closest data grid points have been found using a pre-generated search. This pre-generated search is done by running Algorithm 7 once for each sailing leg and each ship type available. During these runs, the closest point pairs have been stored. In this way, there is no need to search through all data points in each iteration when simulating a solution. Instead, a data point is looked up directly before the search in time is done, greatly increasing computational efficiency.

When finding the nearest data grid point, there will be a certain distance error between the observation point and the data grid point. The maximum allowed search error is given by $MaxDist$. If the distance error is more than $MaxDist$, the wave height is set to be zero. Thus the added resistance becomes zero and the speed is set to design speed.

The function `FINDSPEED` takes in the significant wave height and ship type specifications as input arguments and returns the sailing speed according to equation (8.4).

The function `FINDNEXTPOINT` finds the next observation point according to equation (8.7).

8.5.2 Flow Chart for Simulating a Solution

To simulate solutions to the SSP problem, all sailing legs in each route of each solution are simulated. In Figure 8.6 a flow chart shows how this process proceeds. In step 1 the simulation model chooses a solution from the master problem. A week to simulate over is chosen in step 2. In steps 3-5, all routes in the solution are simulated. Step 4 corresponds to running Algorithm 7 for each sailing leg in the route. The speed up policy can be applied in this step. When all routes in the solution are simulated for the given week, synchronization and duration violations can be calculated as shown in Subsection 8.4.1. This is done in step 6. Note that these violations are system specific, i.e. dependent on all the routes in a solution. If any violations occur penalty costs are added to the solution in step 7. The solution characteristics are updated in step 8. If all solutions have been simulated over all weeks in the simulation period, the simulation is finished. This is checked in step 9 and 10.

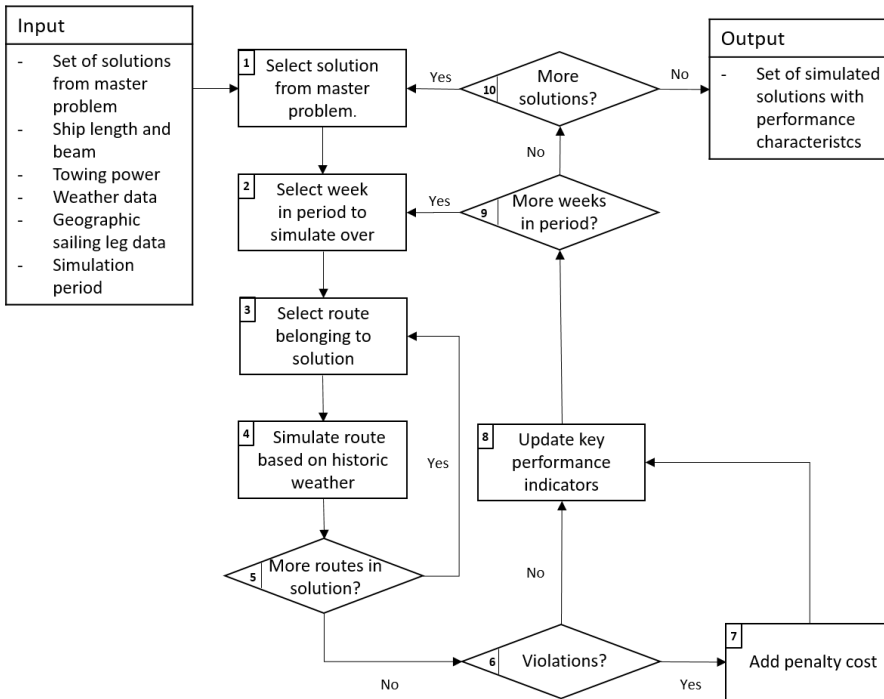


Figure 8.6: Flow chart showing how solutions to the SSP problem are simulated.

As a part of the input to the simulation model, a simulation period is given. The simulation period corresponds to a historical period with weather data, for example the year 2000. For simplicity, it is assumed that one month consists of four weeks. Thereby a year consists of 48 weeks. After every fourth week, the time is reset to the first date in the month. As an example, after 16 weeks the time is updated to be the first day in May. In reality week 16 in a year would be in April. The simplification is convenient when providing statistics on a monthly basis since no routes will have a duration that is split between two consecutive months.

Chapter 9

Data Collection

The available data related to the SSP logistics system are limited, which is natural considering the fact that the system is not yet realized. NCL and SINTEF Ocean have contributed with valuable insight into how the SSP logistics system can be realized, but few specific data values have been provided. Finding accurate data has proven to be difficult, but estimates have been made to the best of the authors' ability.

9.1 Selection of Ports to Visit

The selection of ports to visit along the Norwegian coastline has been made based on the ports NCL currently serves. These ports are the baseline for the overall development of the SSP logistics system and are therefore natural to consider. To create instances that are solvable within a reasonable time, a few ports have been excluded. The excluded ports are either located close to other ports and have a small cargo demand, or they are located too far north for NCL to consider them important for the SSP logistics system. It is worth to emphasize that other ports than the ones currently operated by NCL might be applicable for the SSP logistics system in a more general setting, but with the current selection of ports, it should be possible to gain insight into how the SSP logistics system can be operated.

The ports used in the test instances are shown in Figure 9.1 along with possible locations for ocean hubs. The red dots denote coastal daughter ports and the blue pentagons denote coastal main ports. The continental main port is shown with a green triangle and is chosen to be Maasvlakte located in Rotterdam, Netherlands. Yellow squares denote ocean hubs. Ocean hubs are located according to the following scheme: there is one hub close to each local main port except for the northernmost local main port, and the distances between the hubs are roughly equal. The ocean hubs are located inshore to facilitate as stable ocean conditions as possible when doing transshipments, although this is hard to see in Figure 9.1.

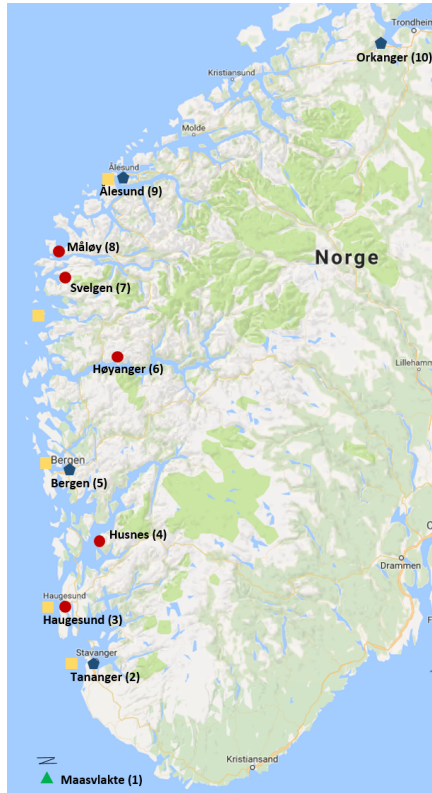


Figure 9.1: Ports chosen for the SSP problem. Red dots denote coastal daughter ports, blue pentagons denote coastal main ports and yellow squares denote ocean hubs. The green triangle is the continental main port Maasvlakte located in Rotterdam, Netherlands.

9.2 Sailing Legs with Geographical Information

The Norwegian Coastal Administration (Kystverket) offers a web-based application called "Kystinfo" (see <http://kart.kystverket.no/>) which contains several features for visualizing geodata. Kystinfo has been used to find and discretize realistic sailing legs.

In Kystinfo AIS, data for container ship traffic in May 2015 can be visualized to view the most used sea lanes. A feature in Kystinfo makes it possible to draw line segments between user defined points on the map. These points can be interpreted as waypoints on a sailing leg. Thus a sailing leg can be discretized by drawing lines on top of the most used sea lanes. Figure 9.2 shows a map from Kystinfo showing a section of the Norwegian west coast. The green lines are AIS data and the blue line is drawn to represent a typical sailing leg between Tananger and Bergen port.

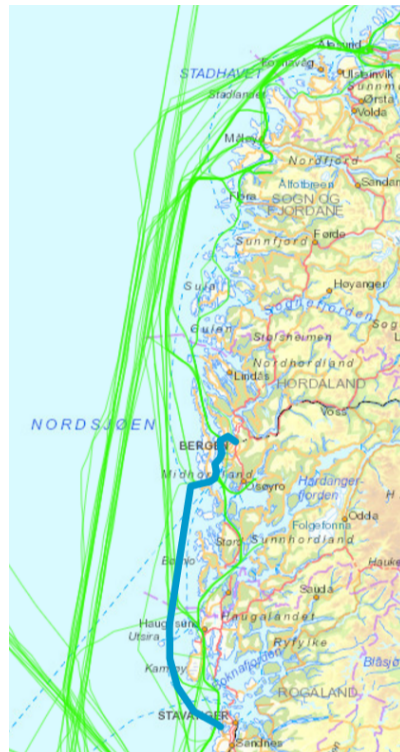


Figure 9.2: Map from Kystinfo showing a section of the Norwegian west coast with AIS data as green lines for container ship traffic in May 2015 and a blue line which represents a typical sailing leg between Tananger and Bergen port that is drawn with the line tool feature.

By using the drawing tool in Kystinfo all sailing legs have been discretized. With 15 ports, the number of sailing legs becomes $(15^2 - 15)/2 = 105$. All sailing legs are obtained at the best of the authors' ability based on what seems reasonable according to the AIS data from Kystinfo. It must be emphasized that a shipping company might use other sailing legs based on operational considerations regarding ship navigation. However, taking this into consideration is beyond the scope of this Master's thesis.

The discretized sailing legs have been downloaded from Kystinfo in a .txt file with a WKT format. The WKT format (well-known text) is commonly used for representing vector geometry objects on a map. The coordinates of each waypoint have been converted from Cartesian projection to a latitude and longitude projection. (More specifically the coordinates are converted from a "EPSG:32633" format to a "WGS 84" decimal format using a python script found in the attached code). With a latitude and longitude projection, the sailing legs can easily be plotted in MatLab. To illustrate, Figure 9.3 shows all sailing legs connected Tananger port.



Figure 9.3: Sailing legs connected to Tananger port.

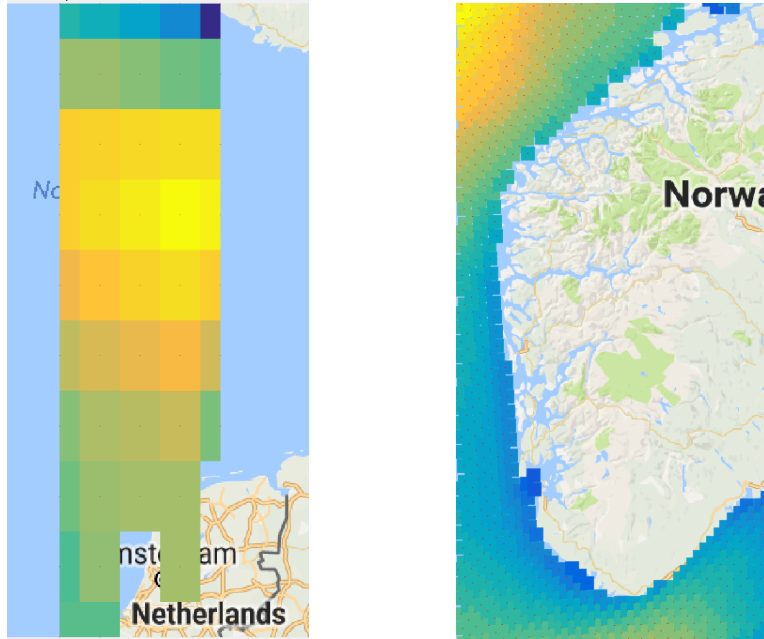
9.3 Weather Scenarios

The weather data is obtained from both European Centre for Medium-Range Weather Forecasts (ECMWF) and the Norwegian Meteorological Institute. Between Maasvlakte and a latitude of 57.5° N, data from ECMWF is used. For latitudes higher than 57.5° N, data from the Norwegian Meteorological Institute are used. It is important to notice that no data points are available inside fjords or very close to land. If a ship is in an area with no closely located data points, its speed is set to design speed.

The data set used from ECMWF is called "ERA-Interim" and is downloaded as a GRIB-file from their website <http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/> (19 March 2017). The GRIB format is commonly used in meteorology to store weather data. The files are read using an external toolbox called "NCtoolbox" in MATLAB. The data set is based on climate reanalysis which gives a numerical description of the recent climate, produced by combining models with observations. Data are available for the years between 1987 and 2016 with a time increment of 6 hours. The resolution of the grid is $0.75^\circ \times 0.75^\circ$. Figure 9.4a shows a visualization of the data. It can be seen that the resolution of the grid is too low to be used for ships sailing close to coastlines. For this reason, the data set from Norwegian Meteorological Institute is used along the Norwegian west coast.

The data set from the Norwegian Meteorological Institute (MET.no) is made available in a custom text file format. Data is available for the years between 1987 and 2016

with a time increment of 3 hours. The resolution of the data grid is approximately $0.3^\circ \times 0.15^\circ$. It should be noted that the accuracy of the data decreases somewhat for grid points close to the coastline. Figure 9.4b shows a visualization of the data. When compared to the sailing legs shown in Figure 9.3 it becomes clear that the data grid resolution is high enough to capture weather effects on most sailing legs as long as they are not too close to the coastline or inside fjords.



(a) Data grid for the ECMWF data which is used between Maasvlakte and a latitude of 57.5° N.

(b) Data grid for the data from MET.no which is used between latitude of 57.5° N and the Norwegian coastline.

Figure 9.4: Data grids used for weather simulation.

9.4 Ship Particulars

The possible capacities for the daughter ships have been chosen to be 100, 200 and 300 TEU. These capacities reflect a range of approximate capacities that might be suitable for the SSP logistics system. A TEU (twenty-foot-equivalent) is a unit of cargo capacity used to describe the capacity of container ships and container terminals, and one TEU is approximately the volume of a twenty-foot container. To find data related to the mother ship, it has been assumed that a mother ship has a capacity of 2500 TEU, which is in accordance with NCL's current plans.

The service speed, also referred to as design speed, for all vessels is 12 knots.

MAN Diesel & Turbo (2009) provides, among else, statistics on propulsion power and ship geometry for container ships based on TEU size and ship speed. In addition, Otto (2013) and Levander (2006) provide detailed statistics for container ships (and other

ship related statistics as well). These sources have been used to provide estimates on ship geometry and propulsion, even though ships with capacity below 300 TEU are not well represented in the statistics.

The beam of the daughter ships with capacities 100, 200 and 300 TEU is set to 15, 16 and 17 meters, respectively. The length of the daughter ships is set to be 90, 95 and 100 meters. For the mother ship, the beam is set to 32 meters and the length is set to be 215 meters. No statistics on bow length has been found, but it is assumed that the bow length for each ship is 10% of the overall length.

The towing power is set to be 1,500, 2,000 and 2,500 kW for the daughter ships of size 100, 200 and 300 TEU, respectively. For the mother ship, the towing power is set to be 10,000 kW. When the speed-up policy is applied, both mother and daughter ships are allowed to increase their power by 25%. The possible power increase is based on the fact that container ships usually operate at a power somewhat lower than their maximum power. The ships can increase power in all weather conditions.

To obtain bunker consumption rates [Wigforss \(2012\)](#) has been used as a benchmark for the daughter ships, and [Notteboom and Vernimmen \(2009\)](#) has been used as a benchmark for the mother ships. When sailing at design power, the bunker consumption rate has been set to 0.5, 0.6 and 0.7 tonnes/hour for a 100, 200 and 300 TEU daughter ships, respectively. For the mother ship, a bunker consumption rate of 1.5 tonnes/hour is used. When using speed-up, a power consumption increase of 0.3, 0.3 and 0.4 tonnes/hour is assumed for the daughter ships with capacities 100, 200 and 300 TEU, respectively. For the mother ship, the increase in fuel consumption is assumed to be 0.6 tonnes/hour.

For all ships, the cargo handling rate in the continental main port is set to be 20 TEU/hour, and in coastal ports, it is set to 15 TEU/hour. For the ocean hubs, two cases are considered: a cargo handling rate of 10 and 50 TEU/hour. The first case represents a situation in which it is difficult to handle cargoes at a higher rate than in a conventional port. The second case represents a situation in which the conceptual cargo handling system NCL considers gives a higher cargo handling rate than in conventional ports.

Overall, the ship specific data values obtained have been considered as reasonable approximations at the given design stage by the ship designers related to the SSP logistics system.

9.5 Cost Parameters

Bunker costs, port costs and time charter costs are dependent on market conditions and can vary substantially. In addition, these costs vary according to ship size, and an important measure in this regard is dead weight tonnage (DWT). DWT expresses how much mass a ship can safely carry excluding the weight of the ship itself. To find roughly DWT measures related to the TEU size of a ship, NCL's current fleet has served as a benchmark in addition to a brief web search for ships of different sizes. Based on this, it has been easier to find appropriate data values.

The weekly time charter cost for a mother ship is set to be 25,000 USD. For daughter ships it is set to be 12,000 USD, 14,000 USD and 16,000 USD for a 100, 200 and 300

TEU daughter ship, respectively. These time charter costs are based on estimates according to various web searches comparing time charter rates with TEU size.

The bunker price used is roughly based on the market price in January 2017 in Bergen port for LSMGO (Low-sulphur Marine Gas Oil) bunker. The price is set to be 500 USD per tonne. LSMGO bunker satisfies the requirements for sulphur content in the North Sea, which is a sulphur emission controlled area (SECA). Due to environmental protection, ships in such sea areas are enforced to use bunker with a low sulphur content.

To find data related to port visits, [Wangsness and Hovi \(2014\)](#) and [Eidhammer \(2014\)](#) provide useful studies on costs and time usage in Norwegian ports. In addition to these studies, actual cost schemes used by the different ports have been briefly compared to get an overview of port costs. Even though cargo handling time and port costs vary with port location and ship type, this has been simplified and average values are used. The port costs are based on a cost for each TEU handled in port, in addition to a fixed fee for entering a port. Because port fees depend on ship size, the fixed fee is set to be higher for mother ships than for daughter ships. The fixed fee for different daughter ships sizes is assumed to be equal. Even though this might not be completely realistic, it has proven hard to find appropriate cost differences between daughter ship sizes.

It is important to note that when measuring container quantities, it has been assumed that one TEU corresponds to one container. In reality, two TEUs might constitute one forty-foot container size. The time used for cargo handling might be affected by this assumption since it is likely that some forty-foot, but also other, less common, container sizes as well, are handled in addition to twenty-foot containers.

The cargo handling cost per TEU in all ports except ocean hubs is set to be 120 USD. Further, for each port visited that is not an ocean hub, a fixed port fee has been set to 1,000 USD and 2,000 USD for a daughter and mother ship, respectively. Also, in this case, finding appropriate cost differences has been difficult. The fixed fee for visiting an ocean hub is set to zero.

9.6 Cargo Demand

To find data on cargoes transported to and from the Continent, first quarter 2016 data from [Statistics Norway \(2016\)](#) have been used. These statistics summarize cargo transport along the Norwegian coastline. The corresponding values have been modified to create two reasonable test cases as explained below.

To represent a current demand level, it is assumed that NCL transports 40 % of the cargoes reported by SSB. According to NCL, assuming this market share can be a rough, but acceptable estimate. To represent a high demand level, the current demand level is increased by 40%. This demand increase represents the 40% growth forecast for 2040 made in the Norwegian national transport plan 2014-2023 ([Meld.St. 26 \(2012-2013\)](#)). The high demand level represents a situation in which all cargoes are transported on the seaway.

The numbers of cargoes to be transported to and from the Continent are shown in Table 9.1. For all ports, the numbers under the columns *To* represent cargoes going to a given port and the numbers under the columns *From* represent cargoes coming

from a given port. Note that the number of cargoes going to Maasvlakte equals the sum of cargoes coming from all other ports. Similarly, the number of cargoes coming from Maasvlakte equals the sum of cargoes going to all other ports.

Table 9.1

Cargoes transported to and from the Continent.

Ports	Current		High	
	To:	From:	To:	From:
Tananger (2)	126	127	176	178
Haugesund (3)	48	45	67	63
Husnes (4)	20	15	28	21
Bergen (5)	126	105	176	147
Høyanger (6)	17	12	24	17
Svelgen (7)	21	35	29	49
Måløy (8)	64	67	90	94
Ålesund (9)	130	69	182	97
Orkanger (10)	64	55	90	77
Maasvlaakte (1):	530	616	743	862

Chapter 10

Computational Study

In this chapter, the results from the computational study are presented. Section 10.1 describes two different test instances and implementation related settings used to generate results. A study on computational efficiency is carried out in Section 10.2. In Section 10.3 and Section 10.4, results for each of the two test instances are presented and analyzed.

10.1 Implementation

This section describes the different test instances and model settings. In addition, relevant key performance indicators are introduced. The reader is referred to Chapter 9 for a detailed description of the input data.

10.1.1 Test Instances

Two different test instances are used to generate results. The test instances are summarized in Table 10.1.

Table 10.1

Test instances used to generate results.

Instance	Ocean Hub Cargo Handling Rate	Demand Level	Other Restrictions
Current Case	10 TEU/hour	Current	NA
NCL Case	50 TEU/hour	High	Mother ship to Orkanger

The *current case* represents today's situation with regards to cargo handling rates and demand levels. In this case, the cargo handling rate in ocean hubs is set to be lower than in a coastal port. The current demand level is described in Section 9.6 and corresponds to 40% of the cargo flow reported by SSB.

The *NCL Case* reflects a potential future situation. The demand level corresponds to a 40% demand increase from the current demand level. The cargo handling rate in ocean hubs corresponds to the rate that might be achieved with the specially designed SSP cargo handling system. In the NCL Case, port Orkanger must be visited on the main route as this is a possibility NCL wants to evaluate.

10.1.2 Performance Indicators

To evaluate solutions to the SSP problem, several performance indicators are important to consider. The operational cost should be compared to duration violations in order to address the severity of delays at a given cost level. In this regard, *Dur. Fail.* denotes the total number of duration violations, while *Dur. Mag.* denotes the accumulated magnitude in hours of all duration violations during the simulation period. Synchronization violations amplify delays and reduce planned idle time. *Sync. Fail.* denotes the total number of synchronization violations and *Sync. Mag.* denotes the total magnitude in hours of all synchronization violations.

A high number duration violations indicates that the system is often disturbed, and a high magnitude indicates the total extent of the violations. By penalizing duration violation magnitude and by applying performance-improving strategies, preliminary testing show that both the number of and the magnitude of duration violations are significantly reduced.

The ships might utilize their planned idle time to avoid duration and synchronization violations. *Idle. Time* denotes the total planned idle time available on all routes in a solution, while *Idle. Use %* denotes the percentage of the planned idle time which must be utilized for sailing due to delays. More specifically, *Idle Mother* denotes the planned idle time available before the continental main port visit. *Idle Loop 1* and *Idle Loop 2* denote the planned idle time available for the daughter ship before the south-going and north-going ocean hub respectively.

Whenever planned idle time is not utilized for sailing, it may potentially be used for revenue increasing operations, such as local shipping. With local shipping, ships can transport cargoes directly between coastal ports whenever there is available demand. Planned idle time can potentially also be used to include a new port visit or increase port visit frequency.

With a high idle time utilization, less idle time is available for potential revenue increasing operations. In addition to a low idle time utilization, having enough cargo capacity to transport cargoes is vital. In this regard *Capacity %* denotes the maximum cargo utilization of a daughter ship sailing its route.

10.1.3 Model Settings

The simulation period used to generate results consists of the four first weeks in each month from the start of the year 2000 to the end of the year 2001. This means that 96 weeks are simulated. The winter season is defined from October to March, and the summer season is defined from April to September.

When simulating a ship on a sailing leg, the *step distance* is set to five nautical miles. This means that, on each sailing leg, the weather state is updated at the departure port and after every five nautical miles. The *max distance* is set to be seven nautical miles. This means that if no data values can be obtained within a radius of seven nautical miles of the ship's location, the wave height is set to zero and consequently the speed is set to design speed. This is because if no data points can be found, the ship is most likely inside a fjord where the weather conditions are calm.

The penalty cost for a duration violation is set to 10,000 USD per hour based on preliminary testing. Recall that only the magnitude of a duration violation is penalized. The model parameters M^{OH} , ε and M^S is set to 1, 0.02 and 0.01, respectively.

10.1.4 Software

The route generation procedure and simulation model have been implemented using MATLAB version R2016b, 64-bit. The master problem has been implemented with the commercial optimization software Xpress-IVE version 1.24.08, 64-bit, with Xpress Mosel version 3.10.0 and Xpress Optimizer version 28.01.04. All tests have been performed on a computer with a 3.4 GHz Intel Core i7 processor and 32.0 GB RAM running Microsoft Windows 10 Education operating system.

10.2 Computational Efficiency

In this section, the computational efficiency, measured as the total run time of the optimization-simulation framework is tested. The tests are done with the solution triggered feedback approach. For a full description of the iteration process between the master problem and the simulation model, the reader is referred to Subsection 6.2.2.

It should be noted that the master problem is solved for one ship type at a time. Each time the master problem is solved, the output is the n -best solutions with the lowest objective value taking both operational and penalty costs into account. An iteration is done each time the master problem is solved. The iteration process between the master problem and the simulation model continues until the final solution for each ship type is found.

An important trade-off to consider is the number of iterations needed, and the number of evaluated solutions in each iteration. Therefore, in the testing process, the number of the n -best solutions found each iteration is varied. Table 10.2 shows how the solution time changes based on this variation.

In Table 10.2, n is the number of solutions with the lowest objective value found by the master problem in each iteration. *Itr. Needed* gives the number of iterations needed between the master problem and the simulation model. *Route Gen. Time* gives the time used to generate the routes. This time is constant because the same routes are generated. *Mp. Time* shows the total time used for solving the master problem in Xpress Mosel and *Sim. Time* gives the total time used for simulating the solutions in MATLAB. *Total Time* shows the total computational time. The total number of solutions simulated is denoted *Solutions Simulated*.

Table 10.2

Solution times for the solution triggered feedback approach.

n	Itr. needed	Route Gen. Time	Mp. Time	Sim. Time	Total Time	Solutions Simulated
1	75	94	2,855	131	3,080	75
5	19	94	771	149	1,013	89
10	13	94	510	182	786	113
20	9	94	390	246	730	157
30	8	94	417	325	836	206
40	7	94	299	371	763	239
50	7	94	405	473	972	297
75	6	94	312	422	828	381
100	6	94	393	573	1,061	494
150	6	94	678	1,154	1,926	689
250	6	94	1,057	1,542	2,693	1133
500	6	94	1,825	3,536	5,455	2305

As seen from Table 10.2, *Itr. needed* decreases with increasing n . This is because a larger part of the solution space is evaluated in each iteration. The optimal trade-off between iterations needed and n is found for $n = 20$. This gives the least *total time*.

It can be observed that the total time is high for both very low and very high n -values. For low values of n , many iterations are needed and consequently, a lot time is used to solve the master problem many times. For high values of n , the master problem uses a lot time to find a high number of solutions. In addition a significant amount of time is used to simulate more solutions than necessary.

An interesting observation is that even if *Solutions Simulated* increases with n , the total time is not necessarily increasing. Generally, *Sim. Time* increases with an increase in solutions simulated, but *MP. Time* is both a result of how many times the master problem is solved and how many solutions it finds in each iteration. Thus, the total time is a trade-off between time used in different parts of the optimization-simulation framework.

Solutions simulated has an upper bound equal to iterations needed times n . For example, when using $n = 20$, the maximum number of solutions evaluated is $9 \cdot 20 = 180$. The reason why fewer solutions than the upper bound are evaluated is that some solutions are found in previous iterations and therefore not simulated again.

It should be emphasized that overhead time is omitted from the total time shown in the table. The overhead time can be significant and is related to transferring information between the MATLAB and Mosel interface. Regardless of overhead time, the most promising n -value is still 20. Since the characteristics of the solutions, and not the computational time, are the focus in this Master's thesis, decreasing the overhead time has not been a priority.

10.3 Solving the Current Case

In this section, the SSP problem is solved deterministically and the best deterministic solution is simulated. Then, the solution triggered feedback approach is used to solve the current case. Different performance-improving strategies are tested and the results are compared with the best deterministic solution. The solution triggered feedback approach is then compared to a simple solution approach with no feedback between the master problem and the simulation model. Lastly, the most promising solution is analyzed more in detail.

10.3.1 The Cost-Optimal Deterministic Solution

To obtain a comparative benchmark on how uncertainty affects the SSP problem, the cost-optimal deterministic solution is simulated. This is the solution found using only the optimization model, without considering any weather uncertainty. A deterministic solution can be found for each ship type, but the solution with 300 TEU daughter ships has the lowest operational cost and this solution is therefore presented. By simulating the deterministic solution, it is possible to evaluate its real world performance.

Route Network

Table 10.3 provides the routes belonging to the cost-optimal deterministic solution. An "N" or "S" after an ocean hub denotes a north-going or south-going ocean hub, respectively. If there is no letter behind an ocean hub name, it means the ocean hub is the northernmost point on the main route and only visited once per week. Note that all routes are starting and ending in the same port. This is to illustrate that they are sailed as round trips. The routes are shown in Figure 10.1. The red solid line is the main route which continues further south to Maasvlakte port even though not shown in the figure. The blue and pink dashed lines are daughter routes 1 and 2, respectively. The corresponding ocean hubs are marked as squares.

Table 10.3

Routes for the cost-optimal deterministic solution.

Route	Ports Visited
Main Route	Maasvlakte → Hub Tananger N → Hub Haugesund → Tananger → Hub Tananger S → Maasvlakte
Daughter Route 1	Hub Tananger N → Haugesund → Husnes → Bergen → Hub Tananger S → Hub Tananger N
Daughter Route 2	Hub Haugesund → Orkanger → Ålesund → Måløy → Svelgen → Høyanger → Hub Haugesund



Figure 10.1: Routes for the cost-optimal deterministic solution.

As seen from Figure 10.1, the main route is short and there is one long and one short daughter route. Even though the main route is short, two mother ships must be used. Since a mother ship is more expensive in terms of bunker costs and port visits, this can explain why the model prefers a short main route.

Solution Performance

The performance of the cost-optimal deterministic solution is discussed based on the key performance indicators introduced in Subsection 10.1.2. Table 10.4 presents important performance characteristics, and a description of the table is given below.

- *Op. Cost. %* gives the weekly operational cost in percentage. This cost is defined to be 100% for the cost-optimal deterministic solution and corresponds to a weekly operational cost of 457,800 USD.
- *Dur. Fail.* gives the total number of duration violations during the simulation period.
- *Dur. Mag.* gives the total accumulated time in hours by which the ships violates their maximum allowed duration during the simulation period.
- *Sync. Fail.* gives total the number of synchronization violations during the simulation period.
- *Sync. Mag.* gives the total time in hours by which the ships must wait on each other due to synchronization violations during the simulation period.

- *Idle. Time* gives the amount of planned idle time available on all routes in a solution and is based on the idle time the ships would have available if no delays occurred.
- *Idle. Use %* gives the percentage of the planned idle time which must be utilized for sailing due to delays.
- *Ship Size* shows the TEU capacity of the daughter ship type used in the solution.

Table 10.4

Performance characteristics of the cost-optimal deterministic solution.

Op. Cost. %	Dur. Fail.	Dur. Mag.	Sync. Fail.	Sync. Mag.	Idle. Time	Idle. Use %	Ship Size
100	277	45,429	194	14,332	192	82.5	300

The cost-optimal deterministic solution seems hard to implement in practice. Having a total of 277 duration violations for three ships in a time horizon of 96 weeks is not viable for a shipping company. Due to the many duration violations and the high duration magnitude, the ships will often be unable to complete their routes in time. Also, there are problems related to synchronizations in ocean hubs because of the high synchronization magnitude. Additionally, almost all of the planned idle time is used for sailing to mitigate delays.

Figure 10.2 illustrates the development of duration violation magnitude for each week during the simulation period. The magnitude is accumulated, meaning a duration violation for a given week is transferred into the next week. This is because once a ship is delayed in a given week, it must start later the next week.

The different colored lines correspond to the routes in the cost-optimal deterministic solution. The main route is the red line, daughter route 1 is the blue line and daughter route 2 is the pink line.

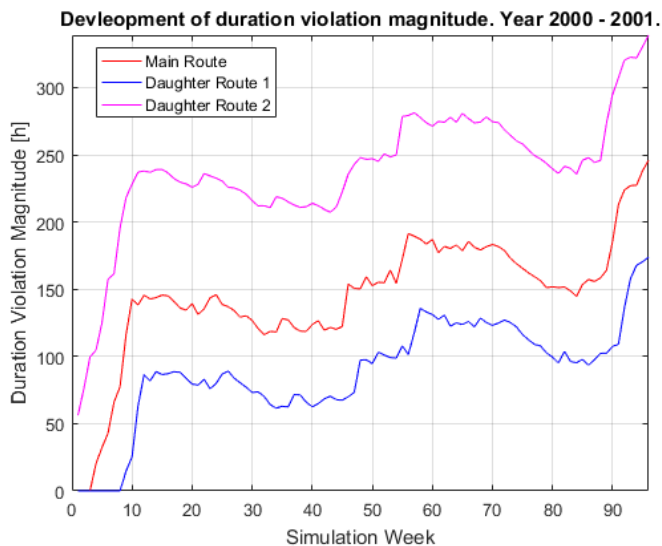


Figure 10.2: Development of duration violation magnitude.

As seen from Figure 10.2, the duration violations for each route have the same pattern, but different magnitudes. The similar pattern occurs because once a ship is delayed, the ship it synchronizes with in an ocean hub gets delayed as well. In other words, a delay propagates as a result of synchronization violations. The difference in duration violation magnitude occurs because the ships sail different routes with a different amount of planned idle available to mitigate delays.

There is clearly a high increase in duration violation magnitude during the winter season (weeks 0-12, 36-60 and 82-96). The rapid increase during the first weeks is because the weather conditions are the worst in these weeks. In the summer season (weeks 13-35, 61-81), the duration violation magnitude decreases on average. The seasonal differences indicate that harsh weather conditions during the winter season give rise to the high duration violation magnitude. If the solution was used only during summer, it seem like the planned idle time could be enough to avoid increasing duration violations.

Recall from Figure 10.1 that the cost-optimal deterministic solution consist of daughter route 1 which is short and daughter route 2 which is very long, in addition to the short main route. In fact, daughter route 2 has very small amount of planned idle time available and thus, duration violations occur easily on this route. The other routes, on the other hand, have large amounts of planned idle time available. However, each week, the mother ship has to wait for the daughter ship sailing daughter route 2 and therefore, duration violations incur for the mother ship as well. This will eventually also affect daughter route 1. These cascading effects coincides well with how the duration magnitude develops for each of the ships as shown in Figure 10.2.

Since daughter route 2 has the highest duration violation magnitude, it is interesting to study this route on an individual basis. Figure 10.3 shows the time it takes to complete one round-trip for each week in the simulation period. Note that delays due to synchronization violations, as well as propagating delays from one week to the next, are *not* included. This means that the figure *only* shows how weather delays in a given week causes daughter route 2 to deviate from its scheduled duration as found in the route generation procedure.

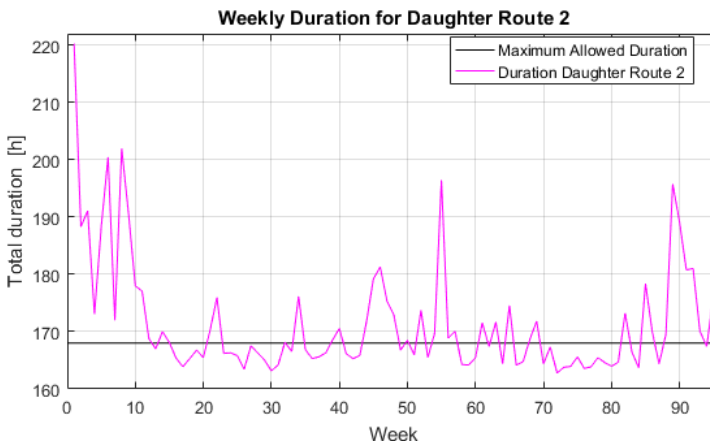


Figure 10.3: Weekly duration *only* taking weather delays into account.

Clearly, as shown in Figure 10.3, in a high percentage of the simulated weeks, the duration exceeds the maximum allowed duration of 168 hours. In the first week, the weather is the worst and this explains the rapid increase in duration violation magnitude shown in Figure 10.2. For the main route and daughter route 1, the maximum allowed duration is never exceeded. Thus it becomes clear that daughter route 2 is not robust and upsets the system as a whole even though the other routes are robust on an individual basis.

Arrival Times in Ports

As a benchmark for comparing solutions, it is interesting to see when the different ships arrive in ports and how they synchronize in ocean hubs. Figure 10.4 shows a box plot of arrival times in ports during the simulation period. The mother ships are originally scheduled to depart from the continental main port in time zero. The arrival times for all ships relates to this departure time. Note that if there has been a duration violation in a given week, it affects the arrival times in the next week. This means cascading effects between the ships as well as propagating effects from one week to another is shown in the figure.

The small vertical line on each box represents the median arrival time. The width of each box corresponds to the interquartile range (*IQR*) defined by the first and third quartile, and accounts for 50% of all port arrivals in the simulation period. The belonging left and right whiskers capture all arrival times within $1.5 \cdot IQR$. Arrival times outside this range are considered outliers and represented with circles.

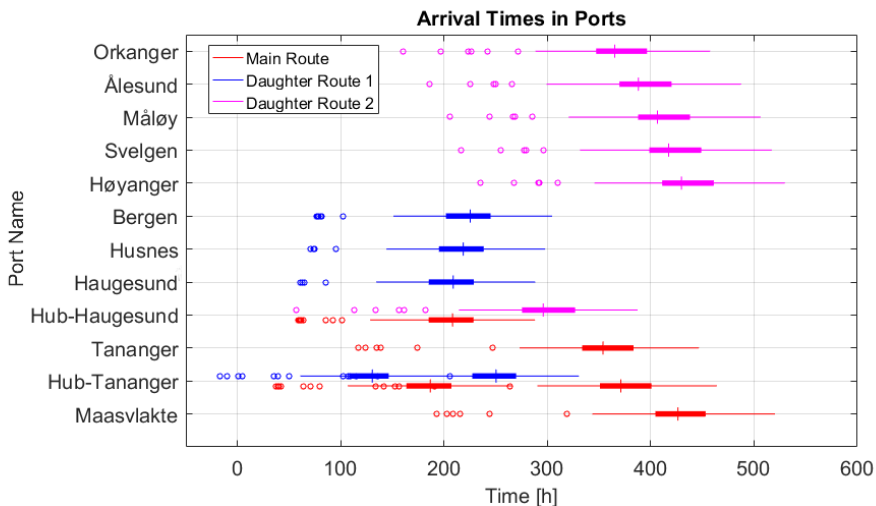


Figure 10.4: Box plot of arrival times in ports.

As seen from Figure 10.4, the arrival times in ports vary greatly within the simulation period. This is because duration violations occur. A duration violation on a daughter route is seen when the daughter ship arrives in an ocean hub later than the mother ship is estimated to arrive in the same ocean hub. Note that this estimate is found in

the route generation procedure. For a mother ship, a duration violation happens when it is not able to complete its route within two weeks (336 hours). It can be seen that the arrival times are often far later than the maximum allowed duration. For instance the median of the mother ship arrivals in Maasvlakte is about 100 hours later than accepted. Clearly, a shipping company would not operate this route network without doing any changes to improve it.

The daughter ships are estimated to arrive in an ocean hub before the mother ship and stay idle until the transshipment. This is often the case for daughter ship 1. This daughter ship waits for the mother ship until it can transship cargoes and then continue sailing. However, daughter ship 2 seems to arrive later than the mother ship in the majority of the simulated weeks. This causes synchronization violations and the mother ship must stay idle and gets further delayed. This observation corresponds well with Figure 10.2, which shows that daughter route 2 is the route with the highest magnitude of duration violations.

As seen in Figure 10.4, the variation in port arrival times is too large to implement the deterministic solution successfully. The solution is not considered robust and it is highly sensitive to uncertainty. This sensitivity can be captured by the simulation model and to find better solutions to the SSP problem, it becomes clear that uncertainty in weather should be taken into account.

10.3.2 The Solution Triggered Feedback Approach

As seen from the evaluation of the best deterministic solution, approaches for finding more robust solutions must be used. In this regard, the solution triggered feedback approach is proposed.

Presenting the Performance-Improving Strategies

The solution triggered feedback approach is tested with different performance-improving strategies to find potentially more robust solutions. The different strategies are listed in Table 10.5.

Table 10.5

List of applied performance-improving strategies

Strategy	Description
None	No strategies are applied.
Slack 10%	10% slack is added on each sailing leg.
Realistic	Sailing times based on a pre-simulation period with 5% extra slack.
Speed-Up	Each ship is allowed to speed up individually on their route.
Seasonal	A tailor-made winter and summer solution is used.
Combined	The <i>Realistic</i> , <i>Speed-Up</i> and <i>Seasonal</i> strategies are applied.

Adding slack is done in the route generation procedure. With the *slack 10%* strategy, a 10% increase in sailing time is added to each leg. This increase is calculated based on the sailing time needed at design speed. Since the average sailing speed will be lower than design speed due to harsh weather conditions, this is taken into account with the *realistic* strategy. With this strategy, statistical weather information is used to find a realistic average sailing speed. The sailing speed is calculated by simulating each ship as they sail on each sailing leg. To avoid back-testing a pre-simulation period between 1998 and 2000 has been used. Then, additional 5% slack is added.

The *speed-up* policy is a recovery-action that can be used during the simulation. Both daughter and mother ships can speed up, but the conditions for when they do so are slightly different. The ships speed up individually if they get delayed by increasing their propulsion power as explained in Section 8.2. When a daughter ship starts sailing its route a given week, it has an initial amount of planned idle time on both loop 1 and 2. If a delay due to harsh weather reduces the planned idle time on either loop to less than one hour, the ship will try to speed up until it has two hours of idle time. Note that a daughter ship will never speed up after it has reached its initial amount of idle time. This means that if a daughter ship has only one hour of planned idle time, it only speeds up until it reaches one hour of idle time. A mother ship tries to speed up if it is more than one hour delayed compared to its expected schedule found in the route generation procedure. Once it has started speeding up, it continues until it is no longer delayed.

With the *seasonal* strategy, the same fleet is used both in the winter and in the summer season. However, the routes sailed by the ships are allowed to change in each season. The seasonal routes are obtained by solving the simulation-optimization framework for each season. Then, seasonal solutions are combined in order to get a whole year solution consisting of the same fleet, but possibly different route configurations.

With the *combined* strategy, the realistic, speed-up and seasonal strategies are applied together. The realistic sailing times used in the combined strategy are specifically adapted to each season during the pre-simulation. This means that more slack will be added in the winter season than in the summer season.

The Solution Triggered Feedback Approach with Different Strategies

The results of using the solution triggered feedback approach with the different performing-improving strategies are given in Table 10.6.

The chosen solutions are based on the lowest total cost returned by the master problem. The total cost consists of the operational cost and the penalty cost. As the penalty cost is fictional and only used to identify low-performing solutions, it is not included in the operational cost when presenting results. However, if speed-ups are utilized, the increased bunker cost is added to the operational cost.

In Table 10.6, *Strategy* shows the performance-improving strategy applied, and *Op. Cost. %* shows the operational cost as a percentage of the operational cost for the cost-optimal deterministic solution, which is 457,800 USD. Otherwise, the description of the table is the same as in Table 10.4. For all strategies considered, two mother ships and two daughter ships are chosen.

Table 10.6

Performance characteristics when using the solution triggered feedback approach.

Strategy	Op. Cost. %	Dur. Fail.	Dur. Mag.	Sync. Mag.	Sync. Mag.	Idle. Time	Idle. Use %	Ship Size
None	102.1	0	0	200	1958	219	14.8	200
Slack 10%	101.4	4	18.7	61	450	171	3.9	300
Realistic	101.4	4	17.1	52	319	162	2.5	300
Speed-Up	102.8	2	4.1	125	927	188	8.9	300
Seasonal	101.5	3	4.3	204	1859	180	17.3	300
Combined	101.2	1	0.7	21	192	160	1.8	300

As seen in Table 10.6, both the number and the magnitude of the duration violations decrease greatly for all strategies when compared to the cost-optimal deterministic solution from Table 10.4. This indicates that by using the solution triggered feedback approach with different performance-improving strategies, solutions with greater robustness and operational flexibility are found. This applies to all strategies even though different strategies give different performance characteristics.

When the strategy *none* is applied, a solution with a 200 TEU ship is chosen. This is the only strategy choosing a ship size other than 300 TEU. No duration violations are incurred and it might therefore be an attractive solution, even though the operational cost is the second highest. There are many synchronization violations and a high synchronization magnitude, but this does not lead to any duration violations. A reason for this might be because of the high amount of planned idle time.

The slack adding strategies *slack 10 %* and *realistic* have both four duration violations and a similar duration magnitude. With both strategies, there are fewer synchronization violations when compared to the *none* strategy.

The *speed-up* strategy has both a higher operational cost and a larger duration violation magnitude than the *none* strategy. The increase in operational cost is partly due to increased bunker consumption which accounts for 6,505 USD per week on average. It may seem like the *none* strategy is dominant to the *speed-up* strategy because the amount of duration violations is the same while the operational cost for the *speed-up* strategy is higher. However, when speed-ups are allowed, the number and the magnitude of synchronization violations are drastically reduced. Additionally, for the given route composition, the duration violation magnitude would have been higher without the *speed-up* strategy. This indicates that the strategy can be promising for increasing operational flexibility.

When using the *seasonal* strategy, the operational cost is 0.1% higher than for the slack adding strategies, but lower than for the *none* and *speed-up* strategies. The duration violation magnitude is only marginally higher than for the *speed-up* strategy. Recall that no slack is added and that speed-ups are not allowed when using the *seasonal* strategy. This can explain the high number of synchronization failures. The fact that the *seasonal* strategy gives a lower operating cost compared to using no strategies makes it interesting to use in the combined strategy.

The strategy with the lowest operational cost is the *combined* strategy. The cost increase is only 1.1% compared to the cost-optimal deterministic solution, and the *speed-up* cost accounts for 1,023 USD per week on average. This is significantly less

compared to the speed-up policy as a stand alone strategy. The reduced speed-up cost can be explained by the fact that adding slack works as a buffer against delays and thus, a higher delay can be tolerated before a speed-up is needed.

With the combined strategy there is only one duration violation with a negligible magnitude. The number of synchronization violations and the related magnitude is also significantly lower than for the other strategies. The utilization of idle time is also low, meaning that the ships usually arrive at their estimated times found in the route generation procedure. When taking all performance characteristics into account, using the combined strategy seems like a preferred choice for a decision maker.

The Combined Strategy for Different Daughter Ships Types

With the potentially attractive results achieved with the combined strategy, it is interesting to study how the strategy unfolds for each daughter ship type. This is shown in Table 10.7. For a description of the table, the reader is referred to Table 10.6.

The solution with the 300 TEU daughter ship type is already shown in Table 10.6, but re-listed in Table 10.7 for convenience. For all solutions, two daughter ships and two mother ships are chosen. When the daughter ship size decreases, the main route extends further north to visit more coastal main ports. By doing this, the mother ship carries a larger share of the total cargo demand and ensures that the smaller daughter ships have enough capacity to visit the remaining ports.

Table 10.7

Performance characteristics for each different daughter ship type.

Ship Size	Op. Cost. %	Dur. Fail.	Dur. Mag.	Sync. Fail.	Sync. Mag.	Idle. Time	Idle. Use %
100	106.1	0	0	24	1068	243	12
200	102.5	0	0	30	149	190	1.5
300	101.2	1	0.7	21	192	160	1.8

For the 100, 200 and 300 TEU daughter ships, the speed-up cost is 1376, 1385 and 1023 USD per week on average, respectively. When comparing the 100 and 200 TEU daughter ships with the 300 TEU daughter ship, the operational cost increases by 4.9% and 1.3%, respectively. This cost increase is due to a longer main route for the 100 and 200 TEU solutions. Even though both these solutions have zero duration violations, this is only marginally less than the 0.7 hour duration violation for the 300 TEU daughter ship type.

All solutions have a relatively large amount of planned idle time. For the 200 and 300 TEU solutions, slightly less than 2% of the planned idle time is needed for sailing to catch up delays. A low idle time usage indicates that the ships mostly arrive at the estimated times found in the route generation procedure, which can offer reliable port visits. The idle time usage for the 100 TEU daughter ship type is on the other hand somewhat higher, but so is also the total planned idle time. The high idle time usage for this solution can be related to the high synchronization magnitude that occurs.

Overall, the solution triggered feedback approach with the combined strategy seems to find robust solutions for all daughter ship types. Providing one solution for each

daughter ship type enables a decision maker to consider several alternatives according to his/her preferences.

10.3.3 A Simplistic Solution Approach Without Feedback

The solution triggered feedback approach can be compared against a simplistic solution approach in which the master problem is solved once returning only one solution for each daughter ship type. Consequently, there is no feedback between the master problem and the simulation model, and only one solution for each daughter ship type is simulated. As with the solution triggered feedback approach, the solution with the lowest total cost is returned by the model.

Table 10.8 gives the performance characteristics when using the simplistic solution approach. For a description of the table, the reader is referred to Table 10.6. For all strategies considered, two mother ships and two daughter ships are chosen.

Table 10.8

Performance characteristics when using a simplistic solution approach.

Strategy	Op. Cost.	Dur. Fail.	Dur. Mag.	Sync. Fail.	Sync. Mag.	Idle. Time	Idle. Use %	Ship Size
None	102.1	0	0	200	1,958	219	14.8	200
Slack 10%	102.1	0	0	77	678	201	5.4	200
Realistic	102.1	0	0	56	377	190	2.9	200
Speed-Up	103.9	0	0	134	1,118	219	9.4	200
Seasonal	102.1	0	0	200	1,958	219	14.8	200
Combined	101.1	4	7	23	341	165	2.2	300

As seen from Table 10.8, all strategies except the combined strategy give zero duration violations. However, this strategy has the lowest operational costs.

When comparing the results in Table 10.8 with the results of the solution triggered feedback approach given in Table 10.6, it becomes apparent that using no strategies gives the same solution as when using the solution triggered feedback approach. For the other strategies, this is not the case and quite noteworthy a 200 TEU daughter ship is chosen instead of a 300 TEU daughter ship for all but the combined strategy. This might be explained since the 300 TEU daughter ships visit more ports and carry more cargoes due to their higher capacity. Hence the duration of the routes is closer to the maximum allowed duration and the routes are more prone to duration violations. As of this reason it is harder to find a robust 300 TEU solution if only one solution is found for each ship type. With the solution triggered feedback approach, on the other hand, a larger part of the solution space is evaluated making it more likely to find robust 300 TEU solutions.

For the combined strategy, the operational cost is 0.1% higher when using the solution triggered feedback approach compared to the simplistic method. When using the solution triggered feedback approach, however, the duration magnitude decreases from 7 hours to 0.7 hours. This shows that the solution triggered feedback approach can find potentially better solutions than the simplistic solution approach.

10.3.4 Detailed Analysis

As presented in Table 10.6, the solution triggered feedback approach with the combined performance-improving strategy was able to find a well-performing solution with practically zero duration violations at only a slight increase in operational cost. It can therefore be interesting to study this solution more in detail.

Route Network

Tables 10.9 and 10.10 give the port visit sequence for each summer and winter route in the solution. In Figure 10.5 the routes are shown.

Table 10.9

Route composition for the winter season.

Route	Ports Visited
Main Route	Maasvlakte → Hub Haugesund N → Hub Bergen → Hub Haugesund S → Tananger → Maasvlakte
Daughter Route 1	Hub Haugesund N → Husnes → Bergen → Høyanger → Hub Haugesund S → Haugesund → Hub Haugesund N
Daughter Route 2	Hub Bergen → Orkanger → Ålesund → Måløy → Svelgen → Hub Bergen

Table 10.10

Route composition for the summer season.

Route	Ports Visited
Main Route	Maasvlakte → Hub Tananger N → Hub Haugesund → Hub Tananger S → Tananger → Maasvlakte
Daughter Route 1	Hub Tananger N → Haugesund → Husnes → Bergen → Høyanger → Hub Tananger S → Hub Tananger N
Daughter Route 2	Hub Haugesund → Orkanger → Ålesund → Måløy → Svelgen → Hub Haugesund

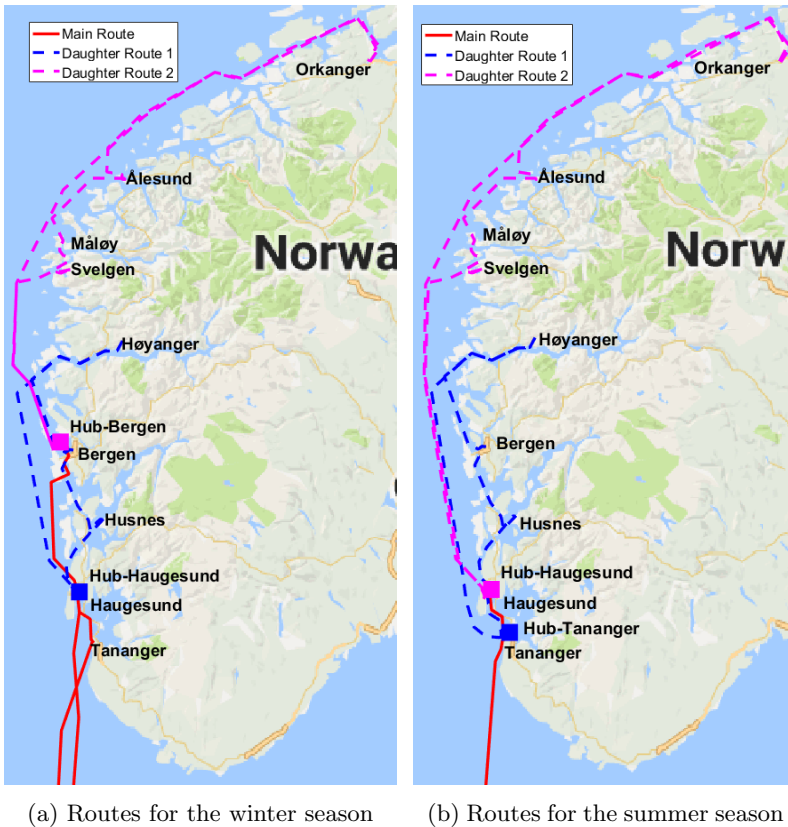


Figure 10.5: Visualization of the routes.

As seen from Figure 10.5, the main route extends further north in the winter season than in the summer season. Compared to a daughter ship, a mother ship is more expensive in terms of bunker and port costs, but by having a mother ship sailing further north, the daughter ships reduce their total sailing distance and get more planned idle time. This is beneficial during the winter season since the weather conditions are rougher and a greater buffer against delays is needed to avoid duration violations. In the summer season, the weather conditions are better and this allows for a shorter main route with corresponding longer daughter routes to reduce operational cost.

Compared to the cost-optimal deterministic solution, the number of port visits are more evenly distributed between the daughter routes. This avoids having one long daughter route with a small amount of idle time that is prone to duration violations.

Detailed Performance Characteristics

Tables 10.11 and 10.12 provide detailed performance characteristics for the winter and summer solution, respectively. The tables specify the amount of planned idle time available for each ship as well as cargo statistics. Detailed information about idle time and cargo statistics enable a decision maker to plan how a ship potentially can be utilized when it is idle.

In the tables, "D1" and "D2" correspond to daughter route 1 and 2, respectively, while "M" corresponds to the main route. A further description of the table is given in the list below.

- *Idle Mother* is the planned idle time in hours on the main route. This is the idle time available before the continental main port visit.
- *Idle. Loop 1* is the planned idle time in hours per week on loop 1 for a daughter ship. This is the idle time available before the *south-going* ocean hub visit.
- *Idle. Loop 2* is the planned idle time in hours per week on loop 2 for a daughter ship. This is the idle time available before the *north-going* ocean hub visit. If the value is "na" a daughter ship meets a mother ship in the northernmost point on the main route.
- *Idle. Use %* gives the percentage of the planned idle time which is utilized for sailing due to delays.
- *Capacity %* gives the maximum cargo utilization for a daughter ship during its voyage. This key value is not applicable for a mother ship since it is assumed to be uncapacitated.
- *Cargo Share %* gives the percentage of total cargo demand in coastal ports transported by a given ship. As an example, if the total cargo demand in coastal ports is 50 and a ship handles 25 of these cargoes, then the cargo share is 50%.

Table 10.11

Detailed performance characteristics for the winter solution.

Route	Idle. Mother	Idle. Loop 1	Idle. Loop 2	Idle. Use %	Capacity %	Cargo Share %
M	72	na	na	0	na	22
D1	na	12	57	5	70	34
D2	na	13	na	5	93	44

Table 10.12

Detailed performance characteristics for the summer solution.

Route	Idle. Mother	Idle. Loop 1	Idle. Loop 2	Idle. Use %	Capacity %	Cargo Share %
M	91	na	na	0	na	22
D1	na	11	57	3	70	34
D2	na	10	na	0	92	44

As seen from Tables 10.11 and 10.12, the characteristics are quite similar across seasons except from the fact that a mother ship has 19 hours more planned idle time during the summer. Since the main route is shorter in the summer season, this explains the increase in planned idle time. Additionally, less slack is added during the summer season as realistic sailing times are used in the combined strategy.

The mother ship has zero idle time utilization in both seasons which means that no planned idle time is needed for sailing. Since no planned idle is utilized, the amount of slack added might be overly conservative. However, it makes sure the whole amount of planned idle time potentially can be used for revenue increasing operations.

The cargo capacity and the cargo share is identical for each ship during both the winter and summer season. This is because each ship visits the same coastal ports. Only the ocean hub visits are changed between the seasons.

The mother ships transport 22% of the total cargo demand in the coastal ports by visiting Tananger. It should be emphasized that a mother ship must also handle all the cargoes from the daughter ships in the ocean hubs. By having the mother ships visiting a coastal port, the cargo capacities needed on the daughter ships are reduced. It also reduces the amount of cargo handling time needed for the daughter ships as the amount of cargoes transported directly by the mother ship do not need to be transshipped in ocean hubs. Each transshipment gives rise to an intermediate cargo handling step which both mother and daughter ships must spend time on. As cargo handling time constitutes a large share of the total duration of a route, it is important to be aware of this effect.

For both daughter ships, only 5% of the planned idle time is needed for sailing in the winter season, and in the summer season, the idle time utilization is even lower. For daughter route 1, there is a substantial amount of planned idle time available in both the winter and summer season on loop 2. As the maximum cargo capacity utilization is 70%, there is cargo capacity available which might be used for revenue increasing operations. For daughter route 2 there is only 13 and 10 hours of planned idle time in the winter and summer season, respectively. In addition, the maximum cargo capacity utilization is higher reducing the potential for revenue increasing operations.

Analyzing Port Arrivals

Figures 10.6 and 10.7 show box plots of the arrival time in ports for the winter and summer season, respectively. For a detailed description of what the box plots represent, the reader is referred to the description of Figure 10.4.

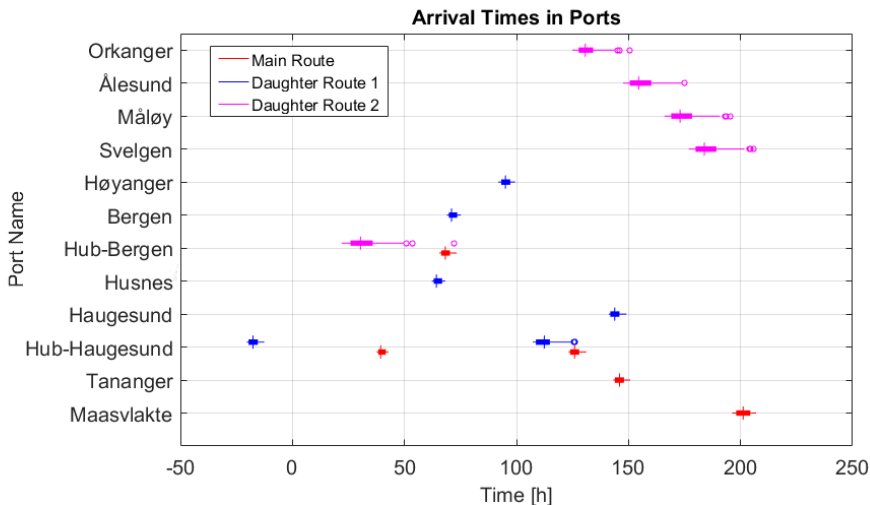


Figure 10.6: Box plot of arrival times in ports for the winter season.

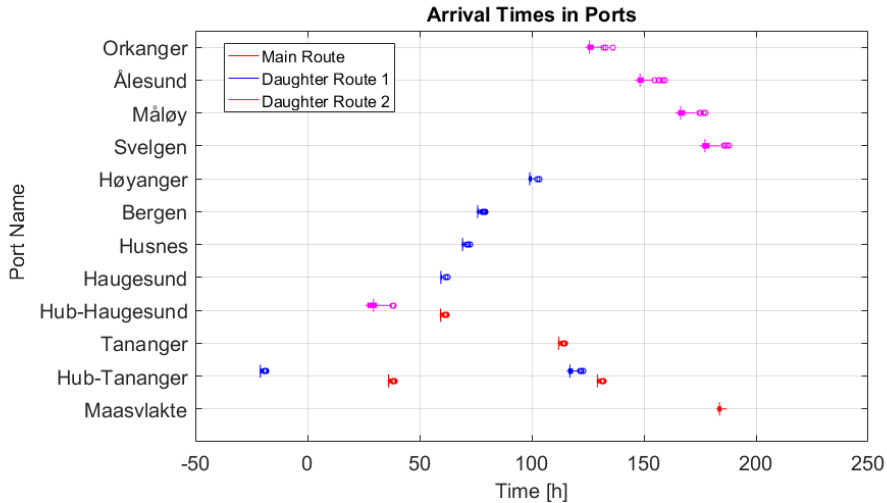


Figure 10.7: Box plot of arrival times in ports for the summer season.

For both seasons, the arrival times are within relatively small intervals. This indicates that both the winter and summer solution is robust and well protected from weather uncertainty.

Especially for the main route and daughter route 1 the arrival time intervals are small. The only exception is daughter route 1 on the sailing leg between Høyanger and Hub-Haugesund during the winter season. On this sailing leg, the daughter ship is somewhat affected by harsh weather and the arrival interval is larger.

For daughter route 2, the effects of harsh weather conditions can be seen particularly during the winter season. The mother ships visit Hub-Bergen at almost the same time every week. The mother ships are also, with one exception, arriving after the daughter ship. This means that the daughter ship departs Hub-Bergen at the same time each week and the increased port arrival interval seen in the following ports is due to weather delays. In one of the weeks, the delay is large enough to cause a duration violation. The rightmost pink circle in Hub-Bergen is after the arrival interval of the mother ship. This means that the daughter ship incurred a duration violation the previous week. Note that a synchronization violation is also incurred this week because the mother ship must wait for the daughter ship. For all other weeks, the arrival of the daughter ship is before the arrival of the mother ship.

In this Master's thesis, an assumption is that a daughter ship can visit a coastal port whenever it arrives and does not need to be there according to an explicitly stated schedule. Nevertheless, having a predictable schedule for arrival times in ports is in the interest of cargo owners. With a predictable schedule they would know when ships will pick up or deliver their cargoes. In this regard, the box-plots of arrival times can be used as a decision-making tool in order to create a schedule for the SSP logistics system. If the time intervals are small, setting a fixed schedule can be fairly easy. This is the case in Figures 10.6 and 10.7, and thus these figures provide valuable insight for a decision maker.

Weather Statistics

As discussed in the previous section, the spread in arrival times are largest for the northern ports during the winter season. This effect can be explained by analyzing the underlying weather conditions. Figure 10.8 shows the average monthly significant wave height along three sailing legs covering the distance from Maasvlakte to Orkanger. Note that the significant wave height is set to zero if a ship sails very close to shore.

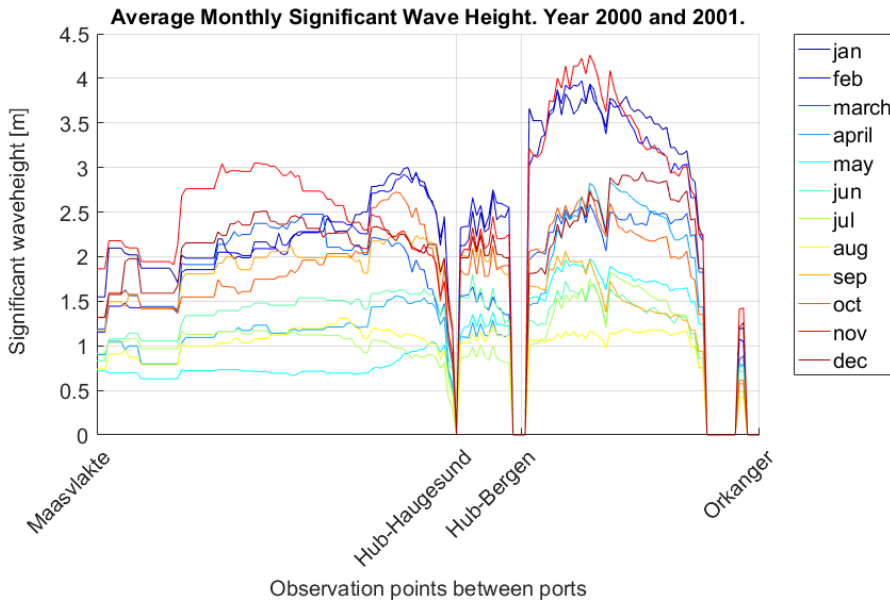


Figure 10.8: Average monthly significant wave height along three sailing legs.

As seen from Figure 10.8, the differences in significant wave height between the months are substantial. The winter months (October to March) have generally higher significant wave height than the summer months (April to September), especially for the sailing leg between Hub-Bergen and Orkanger. In the winter season, this sailing leg is noticeably more exposed to harsh weather than the sailing leg between Maasvlakte and Hub-Bergen.

With the realistic performance-improving strategy, which is included in the combined strategy, this statistical weather information is utilized to provide realistic sailing times. This can be valuable for a decision maker as sailing times can be better estimated and the operation of the SSP logistics system can be more predictable. The differences in weather conditions also justifies why it may be beneficial to sail different routes in the summer and winter season.

10.4 NCL Case

In this section, results for the NCL case (see Table 10.1) are presented and analyzed. Recall that this case represents a future situation foreseen by NCL. The cargo demand is set to high, the cargo handling rate in ocean hubs is set to 50 TEU/hour and the main route must include port Orkanger.

10.4.1 Solving the NCL Case

As the solution triggered feedback approach with the combined strategy provided attractive results for the current case, this approach has also been used to solve the NCL case. The *combined* strategy has also been applied with the simplistic solution approach. For further comparison, the NCL case has been solved deterministically and the solution triggered feedback approach has also been applied with the *none* performance-improving strategy.

Table 10.13 shows how the different solution approaches perform with regards to duration and synchronizations violations as well as idle time utilization. The *deterministic* method refers to the solution found when solving the NCL case deterministically. The *STF None* and *STF Comb.* methods refer to the solutions obtained when solving the NCL case with solution triggered feedback approach (STF) with the *none* and *combined* strategy, respectively. *Simple Comb.* refers to the solution obtained when using the simplistic solution approach with the *combined* strategy.

The operational cost in the table is given in percentage and compared against the cost-optimal deterministic solution for the NCL case. This cost is 585,340 USD per week. Otherwise, the table has the same structure as Table 10.6.

For all but the *STF None* method, only one daughter ship is chosen. With the *STF None* method, two daughter ships are chosen. For all solutions, two mother ships are needed.

Table 10.13

Performance characteristics when using the solution triggered feedback approach.

Method	Op. Cost. %	Dur. Fail.	Dur. Time.	Sync. Fail.	Sync. Mag.	Idle. Time	Idle. Use %	Ship Size
Deterministic	100.0	42	1393	134	849	117	48	300
STF None	103.2	1	7	315	6,773	244	32.3	300
Simple Comb.	100.3	0	0	2	0.8	92	7.7	300
STF Comb.	100.3	0	0	2	0.8	92	7.7	300

The cost-optimal deterministic solution results in a large number of duration violations and does not seem to be viable in practice. However, with the other methods, there is a low number of duration violations something which indicates that the mother ship can possibly sail as far north as Orkanger.

When using the solution triggered feedback approach without performance-improving strategies, only a single duration violation with a magnitude of 7 hours occur. However, this is achieved with a 3.2% operational cost-increase. Additionally, there is a high

amount of synchronization violations and a large percentage of the planned idle time must be utilized to avoid violations. Nevertheless, by evaluating numerous solutions, the solution triggered feedback approach successfully reduces the number of duration violations as intended.

When the *combined* strategy is applied the same solution is obtained both with and without the solution triggered feedback approach. At only a 0.3% operational cost increase 0 duration violations occur. Furthermore, the synchronization magnitude is negligible and the idle time utilization is below 10%.

As in the current case, the combined strategy provides a well-performing solution. In the NCL case, the combined strategy is highly effective even without the solution triggered feedback approach. Even though this approach does not improve results in this specific case when applied together with the combined strategy, it assures that no better solutions can be found. This improves decision support as decisions can be made with improved confidence.

10.4.2 Detailed Analysis

In the following, the solution found with the combined strategy is further analyzed.

Route Network

The same composition of routes is used for both the summer and the winter season. The routes are presented in Table 10.14 and shown in Figure 10.9.

Table 10.14

Routes for both the winter and summer season in NCL case.

Route	Ports Visited
Main Route	Maasvlakte → Hub Haugesund N → Orkanger →
	Ålesund → Bergen → Hub Haugesund S →
	Tananger → Maasvlakte
Daughter Route	Hub Haugesund N → Haugesund → Husnes →
	Høyanger → Svelgen → Måløy → Hub Haugesund S →
	Hub Haugesund N



Figure 10.9: Routes for both the winter and summer season in the NCL case.

As seen in Figure 10.9, the main route includes Orkanger. Note that the main route includes all coastal main ports, thereby saving needed cargo capacity and cargo handling time for the daughter ship. There is no route changes between the winter and summer season. Since the main route must include Orkanger there is no possibility of having a shorter main route in the summer season as it is in the current case. This can explain why there is no difference between the seasons.

Detailed Performance Characteristics

Tables 10.15 and 10.16 show detailed performance characteristics for the winter and summer season, respectively. The table structure is the same as in Table 10.11.

Table 10.15

Detailed performance characteristics for the winter season.

Route	Idle. Mother	Idle. Loop 1	Idle. Loop 2	Idle. Use %	Capacity %	Cargo Share %
M	9.4	na	na	0	na	70
D1	na	44.0	30.6	9.5	81	30

Table 10.16

Detailed performance characteristics for the summer season.

Route	Idle. Mother	Idle. Loop 1	Idle. Loop 2	Idle. Use %	Capacity %	Cargo Share %
M	19.7	na	na	0	na	70
D1	na	44.2	36.5	8.7	81	30

The solution characteristics seen in Tables 10.15 and 10.16 show that the differences between the winter and summer seasons are small. The same routes are sailed both seasons and thus the capacity utilization and cargo share is equal in both the winter and summer.

All coastal main ports are visited on the main route and this makes it possible to use only a single daughter ship. The mother ship has a utilization of 81%, and if it did not visit all coastal main ports, an additional daughter ship would be needed to handle the extra cargoes.

The planned idle time increases from the winter to the summer season. This is because the amount of slack added varies according to season since the weather is expected to be better in the summer. The mother ship has approximately 10 hours less planned idle time during the winter than the summer. However, the planned idle time for the mother ships is not utilized, meaning the realistic sailing times plus the 5% extra slack might be an overly conservative estimate. For the daughter ship, about 10% of the planned idle time is utilized for sailing.

Analyzing Port Arrivals

Figures 10.10 and 10.11 show box plots of arrival times in ports for the winter and summer season, respectively. For a detailed description of what the box plots represent, the reader is referred to Figure 10.4.

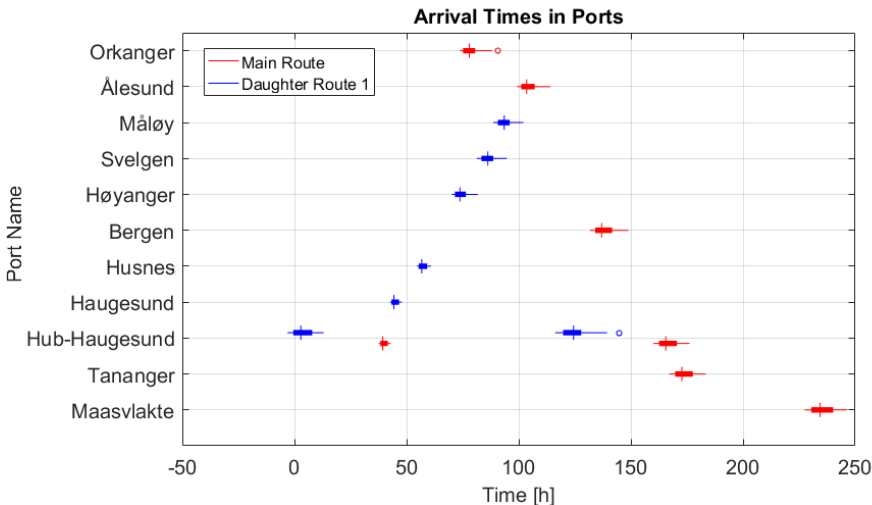


Figure 10.10: Box plot of arrival times in the winter season.

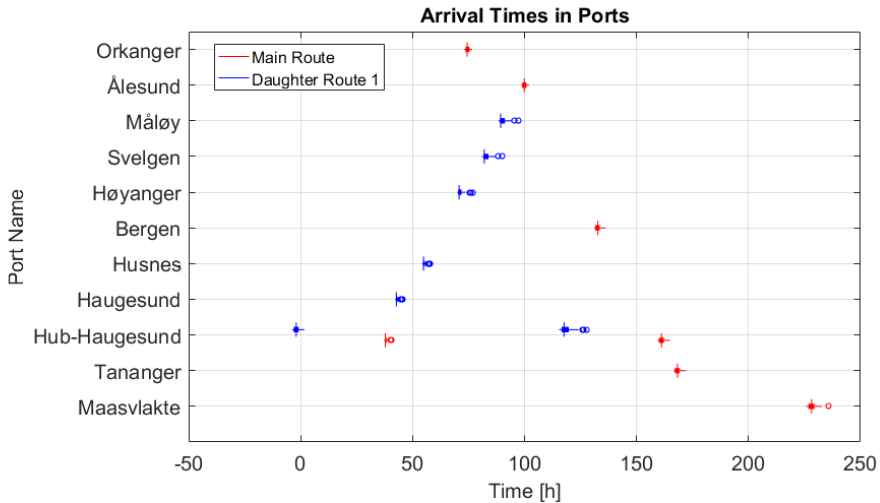


Figure 10.11: Box plot of arrival times in the summer season.

Generally, as for the arrival times in the current case (see Figures 10.6 and 10.7), the arrival interval in each port is small. This clearly indicates that the routes are robust and well protected against weather uncertainty.

For some ports, the arrival times differ slightly in the winter season. This is for example seen for the arrival times of the mother ships in Orkanger. The interval of arrival times in the *north-going* ocean hub visit in Hub-Haugesund is small for the mother ships. This means that the ships depart Hub-Haugesund at approximately the same time each week. The varying arrival times in Orkanger are therefore a result of harsh weather conditions on the sailing leg between Hub-Haugesund and Orkanger, which is in accordance with Figure 10.8. During the summer season, this delay is not apparent, and the time intervals are smaller during this season.

Since the daughter ship always arrives before the mother ship in the ocean hub, synchronizations can be performed without having a mother ship wait for a daughter ship. The two synchronization violations from Table 10.13 is therefore a result of a mother ship being delayed before an ocean hub visit, which causes the daughter ship to wait longer than its planned idle time. This is however not possible to see in the figure because the estimated arrival times from the route generation are not illustrated. In addition, the synchronization magnitude is only 0.8 hours in total and such small variations cannot be distinguished in the figure.

10.4.3 What-If Analysis

It can be interesting to study the implications of relaxing the Orkanger restriction and using different cargo handling rates in ocean hubs. In this subsection, a simple what-if analysis is carried out to study these effects.

With some simple calculations, important insight can be obtained regarding solution outcome. With a *high* demand level, 1605 TEUs are picked up and delivered in total. In the continental main port, $1605 \text{ TEU} / 20 \text{ TEU per hour} = 80$ hours are needed for cargo handling. Given an ocean hub cargo handling rate of 10 TEU per hour and a cargo handling rate in coastal ports of 15 TEU/hour, a mother ship saves time by picking up and delivering cargoes directly in coastal main ports. If a mother ship handles all cargoes possible in coastal main ports, 1123 cargoes are handled in coastal main ports and 482 cargoes are handled in ocean hubs. With the above-mentioned cargo handling rates, 123 hours are needed for cargo handling in these ports. The total cargo handling time on the main route is then $80 + 123 = 203$ hours and consequently, $336 - 203 = 133$ hours are available for sailing. Given a design speed of 12 knots, the mother ship can only reach Ålesund before it must sail south in order to reach the continental main port in time. Clearly, imposing the Orkanger restriction together with a cargo handling rate of 10 TEU per hour is never feasible.

Additionally, since slack is added to the sailing time with the combined strategy, the mother ship might need to turn even longer south. This implies that the daughter ships must serve the northern ports. Since some of these ports, for instance Ålesund, require a high cargo capacity, solutions using 100 TEU and 200 TEU daughter ships might be infeasible even without the Orkanger-restriction.

Table 10.17 presents a simple what-if analysis to find out how the operational cost changes for different cargo handling rates in ocean hubs as well as if the Orkanger restriction is relaxed. The operational cost is given in percentage and compared against the cost-optimal deterministic solution for the NCL case as in Table 10.13. If a solution is not feasible, no cost is shown. In the table, *Cargo Rate* gives the cargo handling rate in the unit TEU/hour, and *To Orkanger* and *No Restriction* indicates whether or not the mother ships must visit Orkanger. The operational cost is shown for each daughter ship type.

All solutions in the table are obtained by using the solution triggered feedback approach with the combined strategy. All solutions have a negligible amount of duration magnitude which indicates that the solutions are robust.

Table 10.17

Operational costs with and without the Orkanger restriction for different ocean hub cargo handling rates.

Cargo Rate	To Orkanger			No Restriction		
	100 TEU	200 TEU	300 TEU	100 TEU	200 TEU	300 TEU
10	-	-	-	-	-	100.3
20	-	-	102.8	-	101.5	100.5
30	-	101.8	100.3	105.2	101.6	100.3
40	103.4	101.8	100.3	103.4	101.7	100.3
50	103.4	101.8	100.3	103.4	101.7	100.3

As seen in Table 10.17, it is not possible to include Orkanger on the main route with an ocean hub cargo handling rate of 10 TEU/hour. Without the Orkanger restriction, a feasible solution is found for 300 TEU daughter ships. With a cargo handling rate in ocean hubs of 20 TEU/hour, it becomes feasible to apply the Orkanger restriction, but only for 300 TEU daughter ships. With a cargo handling rate in ocean hubs of 40

TEU/hour or more, feasibility is ensured for all ship types.

When considering all scenarios, the operational costs turn out to be quite similar. At most, there is a cost difference of 4.9%. A noteworthy observation is that the operational cost actually increases for some scenarios when the cargo handling rate in ocean hubs is increased. This can for instance be seen for the 200 TEU solution without the Orkanger restriction. The reason for this cost-increase is that a higher cargo handling rate in ocean hubs makes the mother ship finish its route faster. This gives the daughter ships less time to finish their routes between the north-going and south-going ocean hub, and with an unchanged cargo handling rate in coastal ports, some daughter routes might not be able to synchronize with a main route anymore.

Overall, the results from Table 10.17 indicate that increasing the ocean hub cargo handling rate does not decrease operational costs substantially, but it can ensure feasibility. Other practical concerns might also substantiate the need for a higher cargo handling rate in ocean hubs, but this is not captured by the model in this given case. It should also be noted that in this what-if analysis, only the cargo handling in ocean hubs are varied. Possibly, other and more cost efficient solutions could be found if the cargo handling rates in the continental main port and in the coastal ports were increased as well.

Generally, a decision maker with a good understanding of the SSP logistics system can use the optimization-simulation framework combined with practical considerations to determine how potential solutions can act in a real life situation. In this regard, a what-if analysis can be highly valuable. An optimal result from the optimization-simulation framework is not necessarily the best solution in real life, but mixed with experience and insight, the modeled solutions can provide additional decision support.

Chapter 11

Conclusion

This Master's thesis has proposed an optimization-simulation framework used to provide decision support in the design of the Short Sea Pioneer logistics system. Potential route networks and fleet deployment plans have been evaluated, with the aim of finding a well performing solution taking weather uncertainty into account.

The optimization-simulation framework consists of an optimization model and a simulation model. The optimization model uses a path flow formulation where routes are generated a priori with a dynamic label setting algorithm. With the routes as input, the master problem selects solutions consisting of a route network with one main route and one or more daughter routes. The solutions are then exposed to realistic weather conditions in the simulation model. The master problem and the simulation model work in an iterative process referred to as the solution triggered feedback approach. With this approach larger parts of the solution space is explored.

To evaluate potential solutions, high performance is indicated by a low operational cost and a low occurrence of duration violations. A duration violation happens if completing a route takes longer time than allowed, disrupting a weekly port visit frequency. Solutions which are affected by duration violations are assigned a penalty cost in the simulation model.

The results shows that weather uncertainty can have a severe impact on the operation of the Short Sea Pioneer logistics system. When simulating the best deterministic solution it has a low operational cost, but a high occurrence of duration violations. The many duration violations make the deterministic solution highly unrealistic to apply in practice.

Several performance-improving strategies were used together with the solution triggered feedback approach to reduce negative implications of harsh weather. The best performing strategy combined the methods of adding slack based on statistical data, using a speed-up policy and the option to sail seasonal routes. The combined strategy reduced the amount of duration violations drastically in exchange for only a small increase in operational cost.

To asses the effect of the solution triggered feedback approach, it was compared against a simplistic solution approach without any iterations between the master problem and the simulation model. For all test cases, the solution triggered feedback approach were able to find as good or better solutions than the simplistic solution approach. As opposed to the simplistic solution approach, the solution triggered feedback approach guarantees that no better solutions can be found based on the trade-off between operational costs and penalty costs.

Two instances were tested, representing a current and future scenario, respectively. The current scenario has a current demand level and a low cargo handling rate. The

future scenario has a high demand level and a high cargo handling rate, and additionally mother ships are forced to visit the northernmost port, Orkanger. For both cases, two mother ships are needed. In the current case two 300 TEU daughter ships were chosen as opposed to only one in the future case. In the current case a short main route was chosen as mother ships have higher operational costs than daughter ships.

The findings in this Master's thesis can provide enhanced decision support in the design the Short Sea Pioneer logistics system. With the proposed simulation-optimization framework, solutions well protected from weather uncertainty can be found at only a small increase in operational cost. This shows that the Short Sea Pioneer logistics system potentially can provide reliable shipping services towards costumers.

Chapter 12

Future Research

Several additional aspects may improve the optimization-simulation framework.

The accuracy of the simulation model could be improved with more specific input data on ship design and weather conditions. Further, additional aspects for handling delays could be considered. If a daughter ship is severely delayed, but another ship has idle time available, port swapping between the ships might be suitable. The delayed daughter ship could potentially also skip a port visit. However, both these methods require more complicated cargo handling logistics. Another alternative could be to move hub visits dynamically to mitigate delays.

It could be interesting to study the implications of introducing time windows in coastal ports. With time windows, the ships must arrive in a port within an explicitly stated time interval. A stochastic approach could be taken in order to find optimal arrival time in ports with regards to delay implications and customer satisfaction. The study by [Zhang et al. \(2015\)](#) which considers flexible time window allocation on a strategic level for a maritime shipping problem could be applicable in this regard.

In addition to weather conditions, demand is another important source of uncertainty that requires attention. Additionally, the expected future increase in demand levels can complicate fleet investment decisions. An interesting avenue for future research could be to formulate a multi-stage stochastic problem in which the route network could change and new ships could be added to the fleet in later stages.

The Short Sea Pioneer logistics system could in general be extended to cover a larger set of ports along the Norwegian coastline. Cooperation between several container shipping companies could for instance make it possible to include ports further north. To study these effects, heuristic methods could be introduced to reduce computational effort as it increases drastically when even a few new ports are added. Heuristic methods should make it possible to effectively find a set of several promising solutions. The concept of Hamming distance, which can be used as measure to capture solution distinctiveness, might be applied to avoid that nearly identical solutions are simulated. As a starting point for such considerations, the study by [Fagerholt, Korsvik and Løkketangen \(2009\)](#) can be built upon.

Generally, since the Short Sea Pioneer logistics system is at a conceptual stage it is important to provide decision support that adhere with strategic concepts. The existing optimization model could be improved by allowing for optional cargoes and port visits, the use of conventional transshipments in larger ports, inclusion of local shipping of cargoes between Norwegian ports and the use of multiple main routes. Nevertheless, maintaining a close dialog with the decision maker is seen as crucial to ensure that the most relevant aspects are considered.

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Appendix A

This appendix shows the formulation of the master problem as presented in Chapter 6. The master problem must be solved once for each available ship type.

Indices:

- p Port.
- m Main route.
- d Daughter ship route.
- s Simulated solution.

Sets:

- \mathcal{P}^{OH} Set of ocean hubs.
- \mathcal{P}^{CD} Set of coastal daughter ports.
- \mathcal{P}^{CM} Set of coastal main ports.
- \mathcal{R}^M Set of main routes. One or two mother ships can serve a main route.
- \mathcal{R}^D Set of daughter routes. A given daughter route d can be served by one and only one daughter ship.
- \mathcal{R}_p^M Set of main routes that includes port p . $\mathcal{R}_p^M \subseteq \mathcal{R}^M$.
- \mathcal{R}_p^D Set of daughter routes that includes port p . $\mathcal{R}_p^D \subseteq \mathcal{R}^D$.
- \mathcal{R}_{pm}^D Set of daughter routes that includes port p and is synchronized to a main route m . $\mathcal{R}_{pm}^D \subseteq \mathcal{R}_p^D \subseteq \mathcal{R}^D$.
- S Set of simulated solutions. If the set is empty, no solutions have been simulated. The size of the set increases for every new solution that is simulated.

Parameters:

- Q^V Daughter ship cargo capacity.
- Q_d^D Cargo capacity needed to serve a daughter route $d \in \mathcal{R}_d$.
- C_m^M Total cost of using a fleet of mother ships on a main route $m \in \mathcal{R}^M$. It includes a weekly time charter cost, bunker costs and port costs.
- C^{TC} Weekly time charter cost of using a daughter ship.
- C_d^{OC} Operating cost for a daughter ship deployed on daughter route $d \in \mathcal{R}_d$. It includes port costs and bunker costs.
- M^{OH} Big-M value that sets the upper limit on how many daughter ships that can visit an ocean hub $p \in \mathcal{P}^{OH}$. If M^{OH} is set to 1, then an ocean hub can be visited by maximum one daughter ship.

- S_{ms}^M Parameter that has the value 1 if a main route m belongs to a simulated solution s , and 0 otherwise.
- S_{ds}^D Parameter that has the value 1 if a daughter route d belongs to a simulated solution s , and 0 otherwise.
- S_s The number of routes which belong to a solution. This can be expressed as follows: $S_s = \sum_{m \in \mathcal{R}^M} S_{ms}^M + \sum_{d \in \mathcal{R}^D} S_{ds}^D$, for each simulated solution s .
- C_s^S The simulated penalty cost of a simulated solution s .
- ε Small value used to express a less than relation as a less than or equal relation. The value can be as small as possible as long as $\varepsilon > 0$.
- M^S Big M-value. The smallest possible value is M^S marginally larger than ε .

Variables:

- x_m A binary variable which takes the value 1 if a mother ship uses main route $m \in \mathcal{R}^M$, and 0 otherwise.
- z_d A binary variable which takes the value 1 if a daughter ship uses daughter route $d \in \mathcal{R}^D$, and 0 otherwise.
- y_s Binary indicator variable which takes the value 1 if a solution has been simulated, and 0 otherwise.

Objective function:

$$\min \sum_{m \in \mathcal{R}^M} C_m^M x_m + \sum_{d \in \mathcal{R}^D} (C^{TC} + C_d^{OC}) z_d + \sum_{s \in \mathcal{S}} C_s^S y_s, \quad (1)$$

Constraints:

$$\sum_{m \in \mathcal{R}^M} x_m = 1, \quad (2)$$

$$\sum_{d \in \mathcal{R}_p^D} z_d - M^{OH} \sum_{m \in \mathcal{R}_p^M} x_m \leq 0, \quad p \in \mathcal{P}^{OH}, \quad (3)$$

$$\sum_{d \in \mathcal{R}_{pm}^D} z_d - \sum_{d \in \mathcal{R}_p^D} z_d \geq M^{OH} (x_m - 1), \quad p \in \mathcal{P}^{OH}, \quad m \in \mathcal{R}^M, \quad (4)$$

$$\sum_{d \in \mathcal{R}_{pm}^D} z_d - x_m \geq 0, \quad p \in \mathcal{P}^{OH}, \quad m \in \mathcal{R}_p^M, \quad (5)$$

$$\sum_{m \in \mathcal{R}_p^M} x_m + \sum_{d \in \mathcal{R}_p^D} z_d = 1, \quad p \in \mathcal{P}^{CM}, \quad (6)$$

$$\sum_{d \in \mathcal{R}_p^D} z_d = 1, \quad p \in \mathcal{P}^{CD}, \quad (7)$$

$$Q_d^D z_d \leq Q^V, \quad d \in \mathcal{R}^D, \quad (8)$$

$$\sum_{m \in \mathcal{R}^M} S_{ms}^M x_m + \sum_{d \in \mathcal{R}^D} S_{ds}^D z_d - M^S y_s + \varepsilon \leq S_s, \quad s \in \mathcal{S}, \quad (9)$$

$$\sum_{m \in \mathcal{R}^M} S_{ms}^M x_m + \sum_{d \in \mathcal{R}^D} S_{ds}^D z_d \geq S_s y_s, \quad s \in \mathcal{S}, \quad (10)$$

$$x_m \in \{0, 1\}, \quad m \in \mathcal{R}^M, \quad (11)$$

$$z_d \in \{0, 1\}, \quad d \in \mathcal{R}^D, \quad (12)$$

$$y_s \in \{0, 1\}, \quad s \in \mathcal{S}. \quad (13)$$