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Liner shipping network design with autonomous vessels

Economic and operational analysis under static and dynamic scheduling

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Abstract

Autonomous shipping technology has seen rapid growth in the last few years. Introduction of autonomous vessels may bring a wide range of benefits to the maritime industry such as cost savings, higher fuel efficiency, emissions reduction, richer data stream. It may also bring changes to the network design. As unmanned ships may allow for more flexibility than conventional vessels, schedules in liner shipping may shift from fixed weekly or biweekly schedules to dynamic ones. This thesis investigates economic benefits of introducing autonomous vessels to the liner shipping network, analyzes how fleet configurations with vessels of different capacity affect the costs and studies effects of a dynamic schedule on both service level and costs. In order to solve the optimization problems, first, a static arc formulation model is presented, and second, a dynamic model with a flexible sailing schedule is introduced. Computational experiments are carried out in three demand scenarios on the benchmark Baltic data instances which are extended to autonomous vessels of three different sizes. The findings show that the introduction of autonomous ships might lead to cost savings due to the decrease in crew costs and bunker costs. The results also suggest that some fleet configurations might perform better due to the asymmetry of the trade. Finally, the implementation of a flexible sailing schedule for autonomous vessels might lead to a great increase in the service level of the network while the costs might not be the lowest.

Keywords: autonomous ships, liner shipping network design, dynamic scheduling.

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List of Abbreviations

DEBRV	Bremerhaven, Germany
DKAAR	Aarhus, Denmark
FFE	Forty-Foot Equivalent Unit
FIKTK	Kotka, Finland
FIRAU	Rauma, Finland
LSNDP	Liner Shipping Network Design Problem
MIP	Mixed-Integer Programming
NOAES	Aalesund, Norway
NOBGO	Bergen, Norway
NOKRS	Kristiansand, Norway
NOSVG	Stavanger, Norway
PLGDY	Gdynia, Poland
RUKGD	Kaliningrad, Russia
RULED	Saint Petersburg, Russia
SEGOT	Goteborg, Sweden
TEU	Twenty-Foot Equivalent Unit
UN/LOCODE	The United Nations Code for Trade and Transport Locations

1 Introduction

1.1 Background

The liner shipping business plays a critical role in the global transportation service industry, which allows international trade of consumer goods between countries and continents. As reported by UNCTAD (2019), “more than four-fifths of world merchandise trade by volume is carried by sea”. Global containerized trade has been growing steadily over the last 25 years (ibid.). High risks, massive financial investments, enormous costs and substantial greenhouse gas emissions are the characteristics of the maritime transportation sector. Thorough planning may lead to both operational costs and carbon emissions reductions.

Operating costs are affected significantly by the design of sailing routes, which is characterized by round-trip, cyclic services at a fixed schedule and transshipment activities. Similar to the public transport system, like bus, subway, train or ferry, the liner shipping business has an arrival and departure schedule with a sequence of port calls and a specific group of similar vessels determined and known in advance for each of its services. How to structure the route network to minimize the total cost is the purpose of the liner shipping network design problem (LSNDP).

Over the last 30 years, the LSNDP has gradually emerged within operations research in maritime transportation. Different researchers have their way to describe the problem; however, the main focus has been similar. The LSNDP can be defined as follows: given a set of demands in a particular planning horizon, a set of ports and a set of vessels with a certain capacity, a set of services is designed to maximize the profit while ensuring that demand and capacity constraints are satisfied. The number of transported containers, their origin and their destination identify a demand. A sequence of visited ports, its order, frequency and employed vessels define a service. The problem’s focus has been on minimizing the total cost of the network, which leads to the maximal profitability for the liner shipping company. Recently, the importance of transit time has been taken into account due to the requirement for service level from customers in the fiercely competing market.

Although based on traditional practices developed over thousands of years, the maritime shipping industry is now at the dawn of a new era. Autonomous vehicles have become a reality in the past decades, having entered such transportation fields as aviation, road and railway transportation.

Autopilot systems have been used in aircraft and trains for many years and are now being developed for road transport by such companies as Tesla, Google, General Motors (Tesla, 2020; Google, 2020; General Motors, 2018). The maritime industry is not an exception.

The idea of a fully autonomous vessel sailing freely at sea in the near future does not seem viable; however, it is undeniable that significant changes towards autonomous shipping have gradually emerged. The number of research publications on autonomous ships has increased rapidly over the last ten years. The Advanced Autonomous Waterborne Applications Initiative started in 2015 with the participation of Finland's academic researchers from the top universities and leading members of the maritime industry aiming to explore different aspects of autonomous shipping. In 2018, the world's first fully autonomous ferry was demonstrated by Rolls-Royce and Finferries in the archipelago south of the city of Turku, Finland (Rolls-Royce, 2016; Rolls-Royce, 2018). The ferry navigated autonomously on one sailing leg whilst the remote control took over the return leg. In November 2020, another autonomous ship, the first zero-emission autonomous container vessel Yara Birkeland, has been delivered from a shipyard to its owner, Yara International, where it will be tested and prepared for operations (Yara, 2020; Marine Insight, 2020).

Autonomy levels in application to machine intelligence and particularly to shipping are considered by different researchers. Rolls-Royce (2016) suggests applying a scale developed by Thomas Sheridan to maritime navigation. The Sheridan scale, which is presented in Appendix A, defines ten levels of autonomy from level 1 when human is in charge of all operations to level 10 when the computer takes over all the decisions and disregards human. Lloyd's Register (2017) defines seven autonomy levels (AL) from a fully manual vessel (level AL 0) to a fully autonomous one (level AL 6), the classification is presented in Appendix B. As noted by Rolls-Royce (2016), a vessel's behavior and a required amount of human's involvement changes depending on different factors such as the state of the vessel and the task being performed.

While there have been multiple research papers related to safety, navigation control, design, project and prototype, only a few works have considered the economics, transport and logistics aspects of autonomous ships (Gu et al., 2019). On the one hand, these papers emphasize the direct benefit of the reduction of crew cost, an advantage of more cargo space and lower fuel consumption. On the other hand, it is more expensive to construct a new autonomous vessel than a conventional one (Danish Maritime Authority, 2016). Port-related costs and monitoring cost from onshore control centers are potentially higher for autonomous ships (Hogg and Gosh, 2016; Kretschmann et al., 2017).

The trade-off between cost savings and additional expenses gives an incentive for liner shipping companies and other key players on the market to take actions towards or against the autonomous shipping trend. In Rolls-Royce (2016), researchers from Turku School of Economics, University of Turku argue that business opportunities perceived by the main actors in the shipping industry are crucial in bringing technological opportunities regarding autonomous shipping into practice.

This thesis will explore potential economic and operational effects of autonomous vessels introduction under a static and dynamic sailing schedule on a case of Regional Baltic Trade which may support the shifting of the container shipping industry towards unmanned vessels. The introduction of autonomous vessels might bring changes to the liner shipping network design. As noted by Christiansen et al. (2019), the network design process could become dynamic for feeder vessels sailing on-demand rather than according to a fixed schedule which would bring more flexibility into the network. This thesis contributes to the existing literature in a way that it is, to the authors' knowledge, the first attempt to apply dynamic scheduling to the liner shipping network design problem.

1.2 Objectives

The aim of the thesis is to explore the potential impact of autonomous vessels introduction on the liner shipping network through formulating the liner shipping network problem, comparing conventional and autonomous fleet and reporting the results on a benchmark suite and the adjusted data for an autonomous fleet. The first research question is as follows:

RQ1: What are the economic effects of shifting from a conventional to autonomous feeder fleet?

In order to answer the question, research on the potential impact from autonomous vessel introduction is conducted, and the analyses are performed on a conventional fleet versus an autonomous fleet with vessels of equal capacity. As the nature of the world trade is asymmetric, fleets with vessels of different capacities might present an advantage for the network, which leads to the second research question:

RQ2: What fleet structure allows to minimize costs of the liner shipping network?

The analyses are performed for different configurations of autonomous fleets, such as a fleet with feeders of the initial size, a fleet of small feeders and fleets of feeders where big vessels are combined with small feeders. As the fleet of small feeders could potentially sail depending on demand, the dynamic model for the LSNDP is introduced and tested in order to answer the third research question:

RQ3: How a dynamic sailing schedule for autonomous vessels affects the total cost and service level of the network?

The same fleet configuration of autonomous vessels is employed for transporting the same amount of demand in two different schedules, i.e. a fixed schedule designed by a static model and a flexible schedule generated by a dynamic model. In this work, service levels of the two networks are measured by the lead time, which is defined as the time span from the point a demand arrives at its original port to the point when its last containers are unloaded at the destination port. The total costs are also taken into consideration; however, the focal point of this part lies in the service level. The dynamic model introduced by this thesis may become a starting point for research on dynamic scheduling within LSNDP and, particularly, within autonomous shipping.

1.3 Structure

The structure of the thesis is given as follows: Chapter 2 elaborates on the business context of liner shipping network design, detailing elements necessary for a deeper understanding of the aspects that have an impact on the LSNDP, i.e. demand, service types, planning horizon and cost structure. Chapter 3 presents a review of existing literature on the LSNDP. In Chapter 4, a static and a dynamic mixed-integer programming (MIP) model for the LSNDP are formulated. Chapter 5 describes the process of data collection for conventional and autonomous fleet, provides details on the Baltic data instances and demand scenarios which will be used for reporting computational results for the purposes of this thesis. Chapter 6 presents the computational study and the experiments' result. In Chapter 7, a discussion on findings from the results, limitations of the thesis and suggestions for future research take place. Chapter 8 concludes the thesis with its most important findings and contributions.

2 Liner shipping network design composition

In this chapter, the essential aspects of liner shipping network domain are described in order to provide readers with a deeper understanding of the business context in application to the LSNDP. Subchapters 2.1 and 2.2 define demand, planning horizon and services. Subchapter 2.3 presents the cost structure of a liner shipping service.

2.1 Demand and planning horizon

The *planning horizon* is of importance since it affects the forecasted demand directly and significantly. The horizon of one week will result in a different demand from that of the horizon of one month. From the market perspective, the *demand* requirement should be fulfilled, which means all the demands should reach their destination. When certain demands in the network are not transported, a revenue loss and possibly a penalty for failing the market expectation should be recognized. The forecasted demand, in its turn, affects the size of the fleet needed to satisfy the network's demands. The estimated demand for container shipping does not only depend on the length of the forecasting window but also on seasonal factors. Seasonality causes variation in the demand for transportation over the span of a year with peaks and troughs. Besides that, seaborne trade and the global economy have effects on the liner shipping business, which results in the fluctuation in demands from year to year.

Different from bulk shipping with a limited number of commodity types that it transports, liner ships transport any types of cargo which can be packed inside a container. Even though all the containers look similar from outside, their contents are various, which then requires different treatments. If the cargo is a low-end product, the shipper is most likely to focus on the price of transportation to reduce their total cost. However, in some cases, late delivery may lead to a more significant loss for the shipper than a little increase in the transportation cost. Then their focus may lay on the lead time metric, rather than the freight rate. Additionally, some cargos are perishable and require cold treatment and limited transporting time. Although in most of the research papers related to LSNDP, demands are treated as an identical cargo, all these elements play a particular role for liner carriers in practice.

2.2 Services

A *service* involves a sequence of port calls at a determined *frequency* with a fixed arrival and departure schedule. It is typically assumed that a service is a round trip where the starting port and the ending port are the same. A service usually has a *weekly frequency*; however, smaller vessels calling smaller ports can have a *biweekly frequency* (Brouer, 2014a). A set of services chosen to operate in a specific market is the backbone of the LSNDP's solution. How many services should be performed in the network? Which ports are included in each service? What are the orders of these ports? How many ships should be employed to serve each service? The answers to these questions affect considerably the total cost of the network, which is the objective of the problem.

There are multiple types of service structure, depending on the number of times a ship visits a port in the service. There are differences in the way researchers define each service type. The categorization of service patterns in this thesis follows Christiansen et al. (2019) as they provide all the fundamental structures that are mentioned in other research papers with clear distinctness among the categories. A service structure can be classified as *a simple* or *circular service, a butterfly service, a pendulum service* or *a complex service*. Which category a service belongs to depends on the presence and characteristics of the butterfly port(s) in that service. Examples of service structures are illustrated in Figure 1 - Figure 4.

When a port gets visited more than once in the same service, it is called a butterfly port. *A simple* or *circular service* allows each port to be called only once, which means no butterfly port is involved in the service. A service with all ports being butterfly nodes is defined as *a pendulum service*, while a service with only one butterfly node is *a butterfly service*. When the butterfly nodes in a service have more than two visits, the service is referred to as *a complex service*.

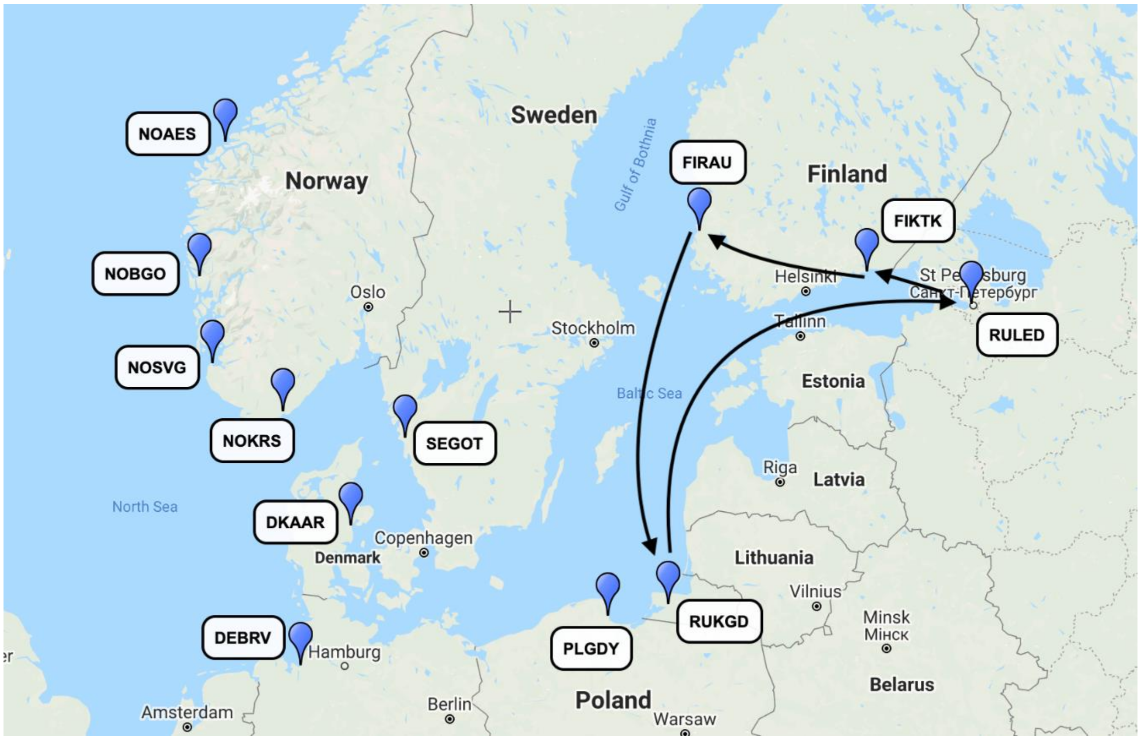

Figure 1. Simple or circular service

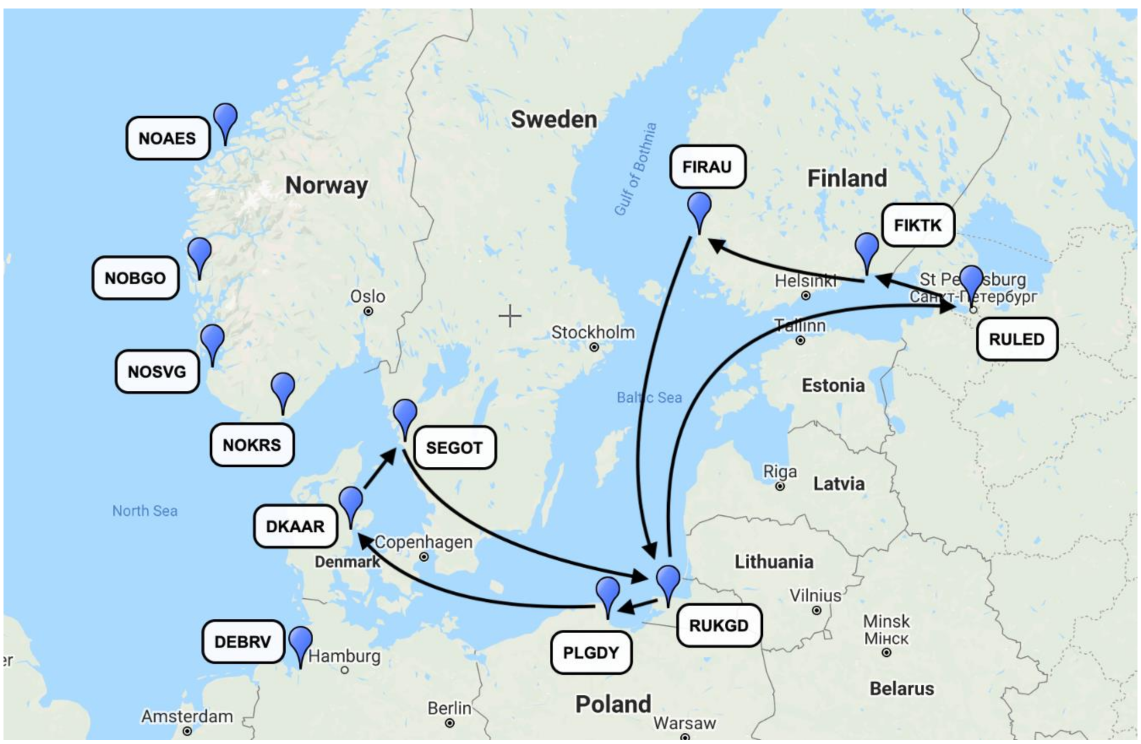

Figure 2. Butterfly service

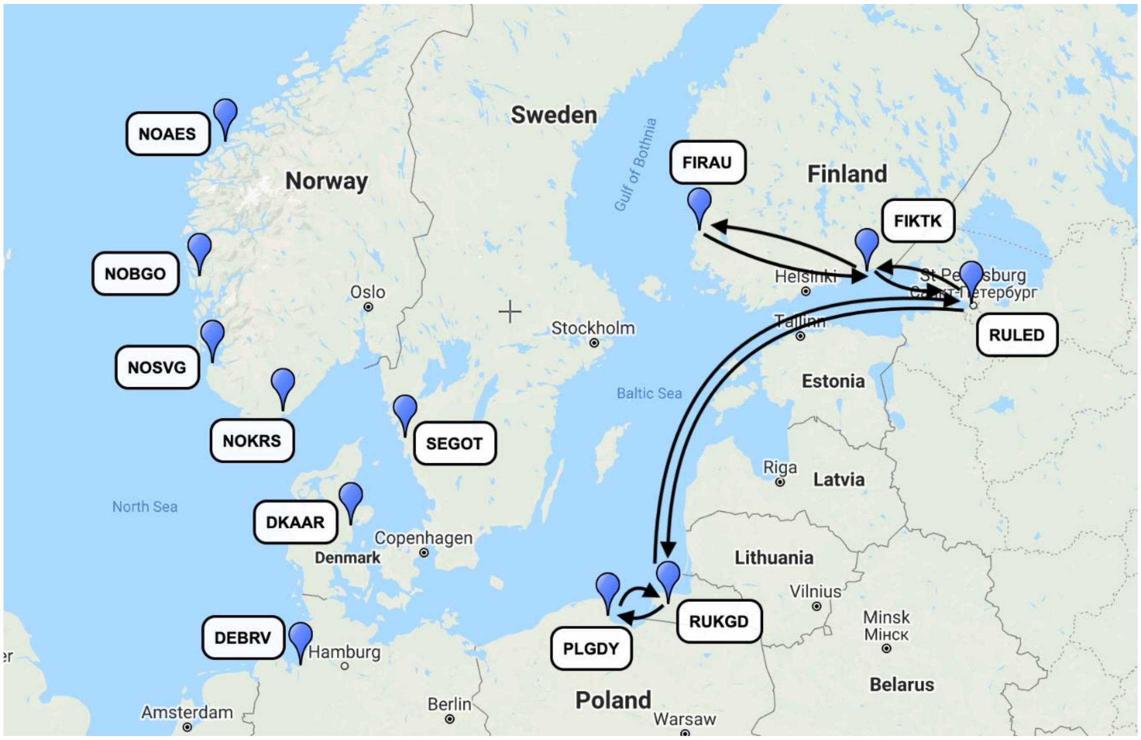

Figure 3. Pendulum service

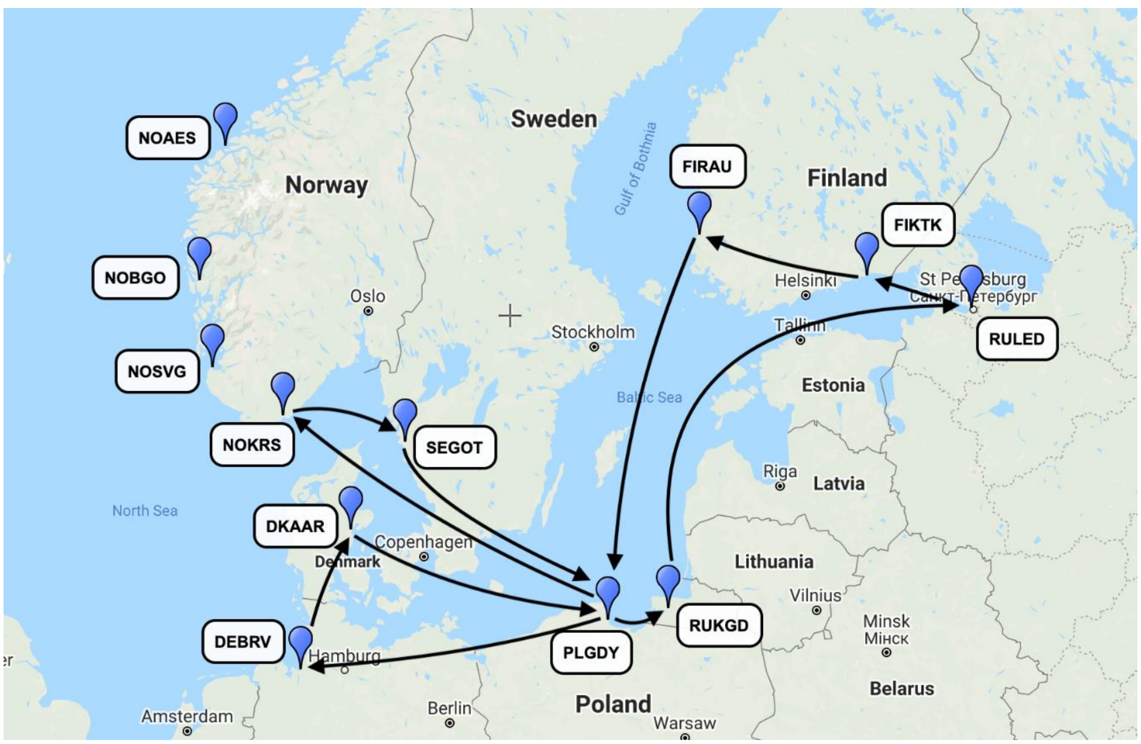

Figure 4. Complex service

The major disadvantage of a network with only simple or circular services is high total voyage cost even though it can be monitored and designed easily. On the other hand, involving more complicated services in the system requires more effort to create and handle the network efficiently; however, the savings on cost and lead time cannot be ignored. Butterfly ports allow *transshipments,* which can reduce the travelling time from a cargo's origin to its destination substantially. Transshipment represents an act of moving containers from one vessel to another in a port (Christiansen et al., 2019) that helps to avoid detours which usually happen with circular services. Transshipment is essential to increase the efficacy of a network but having too many transshipments is also not desirable due to the extra transshipment costs and the network complexity. In practice, there are combinations between simple, circular loops with more complex services in a network.

2.3 Cost structure

Service design is influenced not only by the requirement of demand fulfilment but also by the voyage cost incurred with a service structure. Fully understanding the cost structure of liner shipping business is essential to capture and implement it into the LSNDP model. It is indisputable that the cost structure of the liner shipping business is too complicated such that a solvable model cannot include all these costs. At the same time, a careful pick of costs, which should be accounted for in the LSNDP, is of the essence to ensure that the model is a fair representation of the business.

Stopford (2009) introduces eight building blocks of liner costs to enrich the understanding of the liner shipping service, which is presented in Table 1. Each of the eight blocks concerns a different aspect of the cost dynamics. The first four blocks, including *ship characteristics, service schedule*, *capacity utilization*, and *deployment of containers,* build the framework to perceive the physical aspect of the business. *Ship costs*, *port and charges*, *costs of containers and container handling* blocks provide the economic dimension associated with the four blocks above. Finally, *administration costs* reflect the overhead costs that must be allocated across all the divisions of a liner shipping company.

Table 1. Cost blocks of liner shipping service (Stopford, 2009).

<table>
<tr><td colspan="8">1. Ship characteristics</td></tr>
<tr><td>Ship size</td><td>Design speed</td><td>Design fuel consumption</td><td>Operating speed terminal to terminal</td><td>Fuel consumption</td><td>Time per port call</td></tr>
<tr><td colspan="8">2. Service schedule</td></tr>
<tr><td colspan="4">2.1. Schedule</td><td colspan="4">2.2. Performance Variables</td></tr>
<tr><td>Distance of round trip</td><td>Service frequency</td><td>Port calls on round voyage</td><td>Days at sea</td><td>Days at port</td><td>Total voyage time</td><td>Voyage per annum</td></tr>
<tr><td colspan="8">Required number of ships in weekly string</td></tr>
<tr><td colspan="8">3. Capacity utilization: how full ships are</td></tr>
<tr><td>Head-haul capacity utilization</td><td>Back-haul capacity utilization</td><td>Containers shipped outward</td><td>Container shipped back</td><td>Cargo transported per voyage</td></tr>
<tr><td colspan="8">Annual transport capacity per ship</td></tr>
<tr><td colspan="8">4. Ship costs per day</td></tr>
<tr><td>Operating cost (OPEX) per day</td><td>Capital cost per day</td><td>Bunker cost per day</td><td>Total cost per vessel TEU capacity per day</td></tr>
<tr><td colspan="8">Cost per container transported per annum</td></tr>
<tr><td colspan="8">5. Port and charges (excluding cargo handling)</td></tr>
<tr><td colspan="4">Port cost per TEU</td><td colspan="4">Port cost per call</td></tr>
<tr><td colspan="8">6. The deployment of containers</td></tr>
<tr><td colspan="4">6.1. Mix of boxes needed to operate service</td><td colspan="4">6.2. Efficiency variables</td></tr>
<tr><td>% Ship capacity
TEU’s, FFE’s, reefer containers</td><td>Number of units loaded:
TEU’s, FFE’s, reefer containers</td><td>Total units on full vessel</td><td>Container turnaround time</td><td>Inter-zonal repositioning</td></tr>
<tr><td colspan="8">7. The cost of containers and container handling</td></tr>
<tr><td>Container costs</td><td>Maintenance & repair</td><td>Terminal costs for container handling</td><td>Refrigeration cost for reefer containers</td><td>Transship ment by sea</td><td>Inland intermodal transport cost</td><td>Interzone reposition ing</td><td>Cargo claim</td></tr>
<tr><td colspan="8">8. Administration costs</td></tr>
<tr><td>Administrative productivity</td><td>Number of employees required</td><td>Cost/employee/annum</td><td>Administration cost/voyage</td></tr>
</table>

One of the questions that liner shipping planners would need to answer is which *fleet* they should put in use for the market, including at least three elements: *the number of ships*, *ship size* and *sailing speed.* These factors determine whether liner carriers can fulfil all demands within a given schedule and without excessive waste of capacity. While it is not a good sign to miss the demand requirement, the loss from sailing far below capacity or in ballast too frequently can also be significant. Fleet speed provides the flexibility to adapt to demand fluctuation; for instance, slow steaming when the freight rate and demand are low, or the bunker price is high; or speeding up to exploit the high demand in the peak season. The direct impact of ship characteristics on the voyage cost lies in the bunker consumption. While fuel cost per ton is rather out of control of liner carriers, fuel consumption, to some extent, can be influenced through the choice of sailing speed.

Economies of scale are the main reason for building larger and larger container vessels. Costs associated with ship characteristics like operating costs, capital costs and voyage costs give large ships an advantage in terms of the reduction in cost per TEU. However, the effect of economies of scale is gradually diminishing when the vessel size increases. Additionally, it is incredibly costly to sail an empty or half-filled giant ship. Some may argue that huge ships can result in diseconomies of scale since they cannot call at small ports; therefore, a system of hub and spokes is required to consolidate enough demands for them at the hub port (Stopford, 2009).

The question of whether it is possible to fill up large ships to realize the benefits of the reduction of cost per TEU is also controversial. It is almost impossible to have full capacity utilization on all sailing routes due to the imbalanced nature of global merchandise trade. A conventional round trip involves a *head-haul leg* and a *back-haul leg*. The head-haul leg, or sometimes called front-haul leg refers to the trading route with higher fill rate and profitability. On the contrary, the back-haul leg is the back-home trip where it is considerably challenging to gather enough demand and freight rate are usually low. Liner carriers always face the problem of lack of demand on their back-haul leg. Stopford (2009) uses the transpacific trade as an example to illustrate these cost blocks with a constant fill rate of 90% on the Eastbound leg and 40% on the Westbound leg. The term *fill rate* in logistics context is defined as “the utilized proportion of the total available load volume, load area, or maximum weight” (Jonsson, 2008). In other words, the fill rate is a measure of capacity utilization. In this Table 1, the terms head-haul and back-haul are used to replace Eastbound and Westbound, respectively, to generalize the cost building-block concept.

Service schedule is the framework of liner shipping which describes the port call frequency, arrival and departure time at each port, and route structure. The service schedule determines the number of ships on each route so that the demands are fulfilled. For example, if a service requires two weeks to finish a round voyage, there must be two ships assigned to the service to ensure a weekly port call schedule. The fleet deployment problem and the service schedule design are inseparable from each other; instead, they have a dynamic relationship where a change in one problem will lead to an adjustment in another. An optimal service schedule should be able to bring the demands in the network to their destination, within an acceptable time window and at the lowest cost. While the first requirement seems to be a fundamental criterium, the two latter do not always go together. The longer the lead time of a shipment from its origin to its destination, the lower the service level is, which results in decreasing customer satisfaction. Fulfilling the maximum lead time condition may result in more cost on liner carriers. Therefore, how to construct the network's service schedule is not only the problem of minimizing voyage expenses but also the question of how to balance between cost and service level.

Another complexity layer of the LSNDP lies in the flow of containers. Empty containers must be relocated to the place where they are needed. Due to the imbalance of containerized product trade, empty containers often end up where the demand for them is low. As it is illustrated by Stopford (2009), the number of containers sent from the Eastbound market is more than double those returned from the Westbound market, which will cause a shortage of available containers for transportation on the Eastbound if there is no repositioning of empty containers. Since it takes time to relocate empty containers, it is necessary to have more containers than the capacity in TEU of sailing vessels in the network. The excess of container stock leads to higher capital costs, and also maintenance and repair costs for containers. These costs are different in every liner shipping company, depending on the proportion of their container stock. Handling costs for on-shipment and empty containers, which consists of loading, unloading and any costs related to storage activities at the port, transshipment and reposition, are out of control of liner carriers. These costs vary considerably among ports, due to the difference in facilities available for these services.

Administration costs do not have any direct attachment to voyage costs or the LSNDP; they represent overhead costs that are allocated to each vessel of a liner shipping company.

3 Literature review

In this chapter, existing research on the liner shipping network design problem is reviewed. Relevant literature is used extensively throughout different parts of the thesis, while the discussion in this chapter emphasizes the contributions of the thesis.

Various papers provide surveys on operations research in the maritime shipping industry. Particularly, Brouer et al. (2014a) and Christiansen et al. (2019) present an in-depth overview of existing models and solution methods for the LSNDP.

A comprehensive representation of LSNDP is introduced by Alvarez (2009). The model includes different vessel types with a discrete set of possible operating speeds, and the optimal speed is selected by the model. Demand can be rejected, which leads to revenue loss and perhaps penalty. Only a few restrictions are introduced on the types of routes that can be generated by the model such as that all routes should be a loop, and their length should be limited by an upper limit. The objective is to maximize the profit of the network. However, as noted by Brouer et al. (2014a), the model cannot account correctly for transshipment costs on butterfly routes.

This issue is solved by Reinhardt and Pisinger (2012) who introduce an arc formulation with butterfly routes and transshipment costs where a model assigns a route to each particular vessel. The authors propose the first exact solution method for a model that accounts correctly for transshipments. A different model is presented by Plum et al. (2014) who introduce a novel service formulation, which is the first one to allow an unlimited number of butterfly ports. While this feature brings the model closer to reality, the authors cannot solve it to optimality.

Brouer et al. (2014a) analyze contributions related to different factors affecting the liner shipping network such as network configurations, bunker price, transit time, competitive position, repositioning of containers, frequency, schedule and present an overview of the domain of liner shipping network design that provides insights on the business aspects of the industry. The authors notice that for many years the research on the LSNDP was limited due to the complexity of the industry and the lack of publicly available data. In order to encourage researchers to explore LSNDP, they introduce a benchmark suite Liner-Lib that can be used for mathematical programming and a simplified formulation of LSNDP based on Alvarez (2009). The MIP formulation presented by Brouer et al. (2014a) addresses butterfly routes, accounts correctly for transshipment costs and handles weekly and biweekly frequencies. A three-indexed formulation is used in order to track the last port visited by a vessel and its next port, which allows ensuring the balance at butterfly nodes. However, the model does not consider several industry-relevant aspects such as maximal transit time, repositioning of empty containers, port productivity, pilot times for berthing and equipment cost.

These aspects are considered in several recent research papers. Transit time restrictions on the cargo flow are introduced later by Brouer et al. (2015), Karsten et al. (2017) in their capacitated multi-commodity network design formulation. Koza et al. (2018) also consider sailing speed optimization in addition to cargo transit time limits. Balakrishnan and Karsten (2017) propose a multi-commodity model with a limited number of transshipments that uses flow variables for each stage of transportation. Limiting the number of transshipments is a common requirement in practice, and the approach presented in the paper contributes to closing the gap between LSNDP and the shipping business. A new model is also introduced by Thun et al. (2017) who allow for all kinds of services without any restriction on the number of times each port can be visited in a service and prove that complex service structures may lead to cost savings.

Repositioning of empty containers is also an important sub-problem of LSNDP as it allows maintaining a balance between demand and supply of containers at ports, which is a something that liner shipping companies have to deal with in reality. Empty containers repositioning adds greatly to the complexity of the LSNDP, it is studied by various researches, i.e. Meng & Wang (2011), Shintani et al. (2007), Dong and Song (2009), Bell et al. (2011), Brouer et al. (2011), Chao and Yu (2012).

The LSNDP is well established in the existing literature; however, research on its application to autonomous shipping is scarce. Only a few papers consider a shipping network with unmanned ships, for instance, Akbar et al. (2020) study introduction of autonomous mother and daughter ships into a liner shipping network. The results of their experiments suggest that the introduction of autonomous vessels leads to a reduction of operating costs, and adaption of complex route structures for unmanned ships contributes further to the cost savings. This thesis, in its turn, aims to apply a flexible sailing schedule to the liner shipping network with autonomous vessels as an introduction of unmanned ships may lead to the higher flexibility of the network due to smaller vessels sailing dynamically (Christiansen et al., 2019). This contributes to the existing literature as the LSNDP is usually based on a fixed weekly or biweekly schedule while in this work, a base model with a dynamic schedule is presented.

Moreover, in this thesis, the benchmark suite Liner-Lib Brouer (2014a), which is used by many researchers for reporting their results, i.e. Plum (2014), Balakrishnan and Karsten (2017), Koza et al. (2018), is extended to autonomous vessels of the same size as in the suite and smaller feeders. The extended data allows to compare costs incurred by the network with conventional ships and autonomous ships and analyze cost benefits of different fleet configurations and may be used for future research in LSNDP for autonomous vessels.

4 Problem and model formulation

In this chapter, the MIP formulation is presented. In subchapter 4.1, the static model with a schedule is introduced. Subchapter 4.2 describes the dynamic model with a flexible sailing schedule.

4.1 Static model with a fixed sailing schedule

4.1.1 Problem formulation

Given a set of ports *P* consisting a set of hub ports *H* and a set of spoke ports *S*, the problem is to design a network consisting of cyclic services where all demands are satisfied, and the total operational costs are minimized over the planning horizon t_{max}. Design of a liner shipping network can be presented with a directed graph, where each port is a node, and an arc *(i,j)* in the set of arcs *A* represents a direct sailing route from port *i* to port *j*. Arc *(i,j)* and arc *(j,i)* do not resemble in the way that they have opposite sailing directions. Demands between ports are denoted by the set *D*. The fleet is heterogeneous consisting of different vessel classes *C* with a corresponding capacity e^c, set of vessels of each class $c \in C$ is denoted by V^c. As vessels of each class have a different design speed, sailing time is defined for each class on each arc as t_{ij}^c. Vessels spend *p* time in a port, and the fuel cost varies for each class when sailing at sea or staying at port, denoted by h^c and g^c, respectively. The quantity of demand $m \in D$ is defined as:

$$b_i^m = \begin{cases} b_i^m > 0 \; if\ port\ i\ is\ the\ origin\ for\ demand\ m, \\ b_i^m < 0 \; if\ port\ i\ is\ the\ destination\ of\ demand\ m, \\ 0\ otherwise \end{cases} \tag{1}$$

Each port has fixed port call costs k_i, variable port call costs q_i and lifting costs l_i, which are associated with the port infrastructure, facilities and location. Daily charter rate of a vessel in class C is f^c, which implies that all vessels in the same class have similar conditions. The number of spoke ports in the network is equal to *n*.

All the demands are known in advance and ready for transportation before the fleet starts sailing. Liner shipping companies, nowadays, can, to some extent, obtain a decent demand forecast due to the improvement of forecasting techniques and the availability of mass of historical data. Market requirements will gradually change; however, it will, in a normal situation, take time before these changes impose a significant effect on the network design solution. Besides that, in static models, it is required that all the information and data are known in advance.

All the demands must be satisfied; in other words, all containers must be brought from their origin to their destination. As discussed in Chapter 2, there are two options regarding the demand constraint; i.e. strict constraints that require that no demands are left at their origin port and soft constraints that allow demand rejection and use penalty to punish liners for rejected demands. While allowing unsatisfied demands will increase the model flexibility and ability to pick the most profitable routes, it is likely to lower the service level and customer satisfaction. In this thesis, the demand for transportation must be fully satisfied.

The question of where the fleet is based at the beginning of the time horizon is not trivial since it can affect the feasibility of the network. In the model, vessels must always depart from the hubs and finish their trip after going back to the hubs. This reflects the round-trip feature of services, i.e. a service must be a loop. This requirement assures the match between the trip pre-condition and post-condition, which allows the network design solution to be applied to new periods with the same length as the planning horizon.

Although transshipment is a common practice among the liner shipping companies, no transshipment is allowed in the model. Involving the transshipment activity will increase the complexity of the model, especially the issue of coordinating the arrival time between vessels at the butterfly ports. The demand subjected to the transshipment must arrive at the connecting port before an assigned vessel comes to pick it up. For the purposes of the thesis that has limited writing time, the possibility of transshipment is removed from the model to avoid the additional complication and ensure the feasibility of the model.

The trip length for a vessel is not more than two weeks, which means a vessel may have either a weekly or a biweekly calling frequency at the hubs. This assumption also implies the service level of maximum two-week transit time. If a vessel has a weekly port call schedule at the hubs, the length of its service is between 6.3 and 7 days. These numbers for vessels with biweekly port call schedule at the hubs are 12.7 and 14 days. The buffer between 6.3 and 7 days in the weekly services and between 12.7 days and 14 days in the biweekly services accounts for unpredictable factors which can influence the duration of these trips, for example, weather, tide condition, port congestion and so on. Besides that, as it is argued by Brouer et al. (2014a), applying a strict requirement of 7 days and 14 days for the two port-call schedules can lead to the rejection of commercially valuable routes that violate the constraints with an insignificant margin. Time at port is set at a fixed amount of time, regardless of vessel types and ports. These practices are similar to what Brouer et al. (2014a) applied in their model.

4.1.2 Mathematical model

The following notations are used for modelling the problem:

Sets

H	Set of hub ports.
S	Set of spoke ports.
P	Set of all ports, $H + S \cup P$.
A	Set of arcs.
D	Set of demands from one to another port.
C	Set of different vessel classes.
V^c	Set of vessels in vessel class *c*.

Parameters

Parameters related to Demands and Ports

b_i^m	Quantity of demand *m* at port *i*. The parameter is positive if *i* is the origin for demand *m*, negative if *i* is the destination, and 0 otherwise.
o_i^m	Binary parameter that is equal to 1 if *i* is the origin of demand *m* and 0 otherwise.
d_i^m	Binary parameter that is equal to 1 if *i* is the destination of demand *m* and 0 otherwise.
p	Time at port for a vessel in days.
n	Number of spoke ports.

Cost parameters

g^c	Fuel cost for a vessel of class *c* while sailing at sea.
h^c	Fuel cost for a vessel of class *c* when staying at port.
k_i	Fixed port call costs at port *i*.
q_i	Variable port call costs at port *i*.
f^c	Daily time charter rate of a vessel of class *c*.

l_i Lift costs at port *i*.

Vessel parameters

e^c Capacity of a vessel in vessel class *c*.

t_{ij}^c Sailing time of vessel in class *c* on arc *(i,j)*.

Auxiliary parameters

t_{max} Planning horizon in days.

r Theoretical service length of a vessel with a weekly port call schedule in days.

β Parameter setting the lower bound of sailing time of a vessel with a weekly schedule.

M A big number.

Decision variables

x_{ij}^{mcv} Quantity of demand *m* carried by a vessel *v* of class *c* on arc *(i,j)*.

y_{ij}^{cv} Binary variable that is equal to 1 if arc *(i,j)* is sailed by a vessel *v* of class *c*, 0 otherwise.

s_{ij}^{cv} Number of sails of a vessels *v* of class *c* on arc *(i,j)*.

u_i^{cv} Integer variable used for sub-tour elimination purposes.

w_1^{cv} Binary variable equal to 1 if a vessel *v* of class *c* has a weekly port call at the hub, 0 otherwise.

w_2^{cv} Binary variable equal to 1 if a vessel *v* of class *c* has a biweekly port call at the hub, 0 otherwise.

Model

The model formulation is presented below, followed by an explanation of the objective function and the constraints.

$$\min \sum_{c \in C} \sum_{v \in V} \sum_{(i,j) \in A} g^c t_{ij}^c s_{ij}^{cv} + \sum_{c \in C} \sum_{v \in V} \sum_{(i,j) \in A} h^c p s_{ij}^{cv} \tag{2}$$

$$+ \sum_{j \in P} \sum_{c \in C} \left(k_j + q_j e^c\right) \sum_{v \in V} \sum_{(i,j) \in A} s_{ij}^{cv} \tag{3}$$

$$+ \sum_{c \in C} \sum_{v \in V} f^c t_{max} \left(w_1^{cv} + 2 w_2^{cv}\right) \tag{4}$$

$$+\sum_{m\in D}\sum_{c\in C}\sum_{v\in V}\sum_{(i,j)\in A} o_i^m l_i x_{ij}^{mcv} + \sum_{m\in D}\sum_{c\in C}\sum_{v\in V}\sum_{(i,j)\in A} d_j^m l_j x_{ij}^{mcv} \tag{5}$$

The objective function minimizes the total operational cost of vessels in operation. The expression (2) captures the costs of bunker fuel that vessels use at sea and port. The next term (3) computes port call costs that include fixed and variable port call costs. The term (4) accounts for time charter costs. If a vessel has a biweekly port call schedule at the hubs, two vessels are needed in order to cover the route and ensure weekly departures. The expression (5) obtains costs of loading and unloading containers at port.

Constraints

Demand constraints

$$\sum_{c\in C}\sum_{v\in V}\sum_{(i,j)\in A} x_{ij}^{mcv} - \sum_{c\in C}\sum_{v\in V}\sum_{(j,i)\in A} x_{ji}^{mcv} = b_i^m, \qquad i \in P, m \in D \tag{6}$$

$$\sum_{(j,i)\in A} x_{ji}^{mcv} - \sum_{(i,j)\in A} x_{ij}^{mcv} + b_i^m d_i^m \leq 0, \qquad m \in D, i \in S, c \in C, v \in V \tag{7}$$

$$\sum_{m\in D} x_{ij}^{mcv} \leq e^c s_{ij}^{cv}, \qquad c \in C, v \in V, (i,j) \in A \tag{8}$$

Constraints (6) ensure that all demands are satisfied. Constraints (7) ensure that there are no transshipments in the network, which means demand *m* will not be unloaded at port *i*, unless port *i* is its destination. The capacity constraints (8) state that the number of containers shipped on an arc must be lower than the capacity of a vessel that sails this arc. The real capacity of a vessel *v* on an arc *(i,j)* may not be the physical capacity of the vessel itself since vessel *v* may sail through arc *(i,j)* for several times during the planning horizon. For example, if the physical capacity of vessel *v* is 450 FFE and it sails through arc *(i,j)* twice, the real capacity of vessel *v* on arc *(i,j)* is 900 FFE.

Route constraints

$$\sum_{(i,j)\in A} s_{ij}^{cv} - \sum_{(j,i)\in A} s_{ji}^{cv} = 0, \qquad i \in P, c \in C, v \in V \tag{9}$$

$$\sum_{j\in S} y_{ij}^{cv} - w_1^{cv} - w_2^{cv} \geq 0, \qquad c \in C, v \in V, i \in H \tag{10}$$

$$u_i^{cv} - u_j^{cv} + (n+1)y_{ij}^{cv} \leq n, \qquad c \in C, v \in V, i \in S, j \in S, i \neq j \tag{11}$$

Constraints (9) are cyclic constraints that ensure that vessels that enter a port leave that port. In order to enforce all vessels to start from the hub ports, constraints (10) are used. Constraints (11) are sub-tour elimination constraints.

Network constraints

$$s_{ij}^{cv} - y_{ij}^{cv} \geq 0, \qquad c \in C, v \in V, (i,j) \in A \tag{12}$$

$$My_{ij}^{cv} - s_{ij}^{cv} \geq 0, \qquad c \in C, v \in V, (i,j) \in A \tag{13}$$

$$\sum_{(i,j)\in A} y_{ij}^{cv} - w_1^{cv} - w_2^{cv} \geq 0, \qquad c \in C, v \in V \tag{14}$$

$$Mw_1^{cv} + Mw_2^{cv} - \sum_{(i,j)\in A} y_{ij}^{cv} \geq 0, \qquad c \in C, v \in V \tag{15}$$

Logic constraints (12) and (13) express the relationship between the number of sails s_{ij}^{cv} and the binary variable y_{ij}^{cv} and allow a vessel to sail one arc multiple times. The two constraints require that either both variable y_{ij}^{cv} and s_{ij}^{cv} are positive, or both are equal to 0. In order to show which vessels are in use, constraints (14) and (15) are used. They state that if a vessel does not sail any arc, it should not be counted as in use and if a vessel sails an arc, it should be considered as in use either on a weekly or biweekly basis.

Schedule constraints

$$w_1^{cv} + w_2^{cv} \leq 1, \qquad c \in C, v \in V \tag{16}$$

$$\sum_{(i,j)\in A} \left(t_{ij}^{c} + p\right) s_{ij}^{cv} - Mw_2^{cv} \leq rw_1^{cv}, \qquad c \in C, v \in V \tag{17}$$

$$\sum_{(i,j)\in A} \left(t_{ij}^{c} + p\right)s_{ij}^{cv} + Mw_2^{cv} \geq \beta r w_1^{cv}, \qquad c \in C, v \in V \tag{18}$$

$$\sum_{(i,j)\in A} \left(t_{ij}^{c} + p\right)s_{ij}^{cv} - Mw_1^{cv} \leq 2r w_2^{cv}, \qquad c \in C, v \in V \tag{19}$$

$$\sum_{(i,j)\in A} \left(t_{ij}^{c} + p\right)s_{ij}^{cv} + Mw_1^{cv} \geq 2\beta r w_2^{cv}, \qquad c \in C, v \in V \tag{20}$$

Constraints (16) ensure that if a vessel sails, it can have either weekly port call or biweekly port call schedule at the hubs. Constraints (17) - (20) express the relationship between sailing time and weekly/biweekly port calls. If a vessel has weekly port calls, w_1^{cv} must be equal to 1 and its sailing time should be between 6.3 and 7 days where *r* is equal to 7, and 6.3 is calculated as the theoretical service length of a vessel with weekly port call basis multiplied by the parameter β equal to 0.9. If a vessel has biweekly port calls, w_2^{cv} must be equal to 1 and its sailing time should be between 12.7 and 14 days which are computed by multiplying the sailing time for weekly basis by two.

Auxiliary constraints

$$x_{ij}^{mcv} \geq 0, \qquad m \in D, c \in C, v \in V, (i,j) \in A \tag{21}$$

$$s_{ij}^{cv}, u_i^{cv} \in \mathbb{Z}^{+}, \qquad c \in C, v \in V, (i,j) \in A \tag{22}$$

$$y_{ij}^{cv}, w_1^{cv}, w_2^{cv} \in \{0,1\}, \qquad c \in C, v \in V, (i,j) \in A \tag{23}$$

Constraints (21)-(23) define the domain of variables.

4.2 Dynamic model with a flexible sailing schedule

In the static model, all the necessary information for designing the network is known in advance; and there is no randomness in the model. The total demand in the network remains the same, and the shipping schedule at each port is fixed with a weekly frequency. This predetermined schedule system leads to the fact that some demands have to wait for their turn to be transported to their destination, which causes long waiting and transporting time and a lower service level. With the introduction of autonomous vessels in the maritime industry, Christiansen et al. (2019) suggest the idea of groups of small autonomous ships sailing in convoy with a dynamic, on-demand schedule for feeder-lines. Demands will not be available at their original port and ready to be loaded at the beginning of the planning period as they are in the static model. Instead, they will appear randomly at different points of time during the planning horizon, which breaks down the ultimate assumption of the static model that all information must be known in advance. The dynamic model in this thesis is an attempt to illustrate the suggestion from Christiansen et al. (2019) to investigate the economic and service level effect of a dynamic sailing schedule.

4.2.1 Dynamic scheduling

In the dynamic LSNDP, the total demand quantity is still deterministic and known in advance; however, as it is mentioned above, the arrival time is different from one demand to another. Demands arrive randomly during the planning horizon. Each demand has the same probability of appearing on any day of the horizon. The demand-arrival schedule is not predetermined. The demand volume arriving at the origin port decides the transport schedule; that is, every day, the total demand available in the network is calculated and compared with a determined threshold to decide whether vessels will sail or not. If the trigger, by any chance, happens to be equal to the total demand of the whole planning period, the dynamic sailing schedule becomes the fixed schedule as the vessels will sail only once, that is, at the end of the planning horizon after all the demands have arrived at their original port. The smaller the threshold is, compared to the total demand of the whole planning period, the more frequently vessels sail, which leads to a shorter waiting time of demands at their departure port but also a risk of high costs due to the lack of consolidation possibilities.

Theoretically, a low possibility of consolidating small shipments into a big package to take advantage of economies of scale in transportation can be a disadvantage of the dynamic sailing schedule in the case there are many small demands in the network. If vessels sail only once a week, all the demands will be available; then there is a higher chance of combining small demands and ship them together, saving costs and having higher capacity utilization. With a dynamic schedule where the decision on the sailing schedule is based on existing demands for transportation every day and a determined threshold, it is not likely that the majority of small demands are available at the same time for the consolidation. The advantage of a dynamic sailing schedule lies in the improvement in service level due to the shorter waiting time that demands spend at their origin ports since vessels will sail whenever the threshold is reached.

The dynamic scheduling in this thesis is not based on real-time demand; instead, the demand volume presented in the network plays the role as a condition to trigger the sailing action. After the decision of putting vessels into operation, new information is no longer updated for the already-made decision. The model is an attempt to move towards an on-demand sailing schedule, in the way that the demand in the network is the decisive factor for when the transportation takes place, not a predefined, fixed schedule. Although the model is not updated continuously with real-time demand, it, to some extent, still reflects the dynamic scheduling aspect with small autonomous vessels sailing in convoys suggested by Christiansen et al. (2019).

4.2.2 Problem formulation

Most of the conditions in the static model remain in the dynamic model, including the requirement for demand fulfillment, vessels' sailing starting point, no transshipment and time at port. The assumption of demand arrival is the most significant change in the model. Not all the demands appear at the beginning of day 1; instead, each of them will arrive in full batch, randomly during the planning horizon. Each demand has a probability of 1 divided by the length of the planning horizon to arrive on any day from day 1 to the last day. The arrival days are drawn from a uniform distribution. All demands from the hubs will be transported on the sailing day so that none of them spends more time waiting if the trigger for sailing is reached. Demands from the other spoke ports would have to wait until a vessel comes to pick them up. These vessels may sail in convoy if the demand is high but may also operate individually in the case of small demands. There is no fixed schedule for port calls at the hubs; vessels sail when the total available demand volume in the network meets a certain threshold.

The model is built on the principle that a dynamic model is a sequence of static models, which means there is a base, static model that solves the problem of designing the network but does not contain any dynamic, random part. The dynamic element lies in the decision on when the static model will be solved, and the network will be constructed. A "for" loop is implemented to go through every and each day of the planning horizon. The "for" loop mechanism is illustrated below.

Illustration of the “for” loop mechanism and “if” condition

for {*t* in 1..last day of the horizon}

Calculate the total available demand in the network on day *t*

if (total available demand in the network on day $t \geq$ trigger) then

solve the base, static model and design services/routes for vessels to sail on day *t*;

set the available demand in the network at the end of day *t* back to zero;

else

demands arriving on day t stay in the network;

the loop moves to the next day.

On each day, the total existing demand in the network is calculated and compared to the predetermined threshold. If the total demand is equal to or higher than the trigger, the base model will be solved, and sailing routes will be designed; then the total available demand in the network will be set back to zero. Otherwise, the loop will move on to the next day without any action, the demand in the network will accumulate until it reaches the trigger again or until it is the last day of the horizon, depending on which condition is met first. On the last day of the planning horizon, all the demands left in the network will be transported, regardless of the trigger.

4.2.3 Mathematical model

As it is explained above, the dynamic model consists of two parts; i.e. the base, static model and the dynamic part performed by a “for” loop and an “if” condition. The “for” loop decides when the sailing day is, using the “if” condition and the given threshold. When the sailing day is decided, it is the job of the base model to design the network, based on the demand volume assigned from the “for” loop.

The base, static model is presented as follows:

Sets

H Set of hub ports.

S Set of spoke ports.

P Set of all ports, $H + S \cup P$.

A Set of arcs.

D Set of demands from one to another port.

V Set of vessels.

Parameters

Parameters related to Demands and Ports

Q^m Quantity of demand *m*.

θ_i^m Quantity of demand *m* at port *i*. The parameter is positive if *i* is the origin for demand *m*, negative if *i* is the destination, and 0 otherwise. The default values are zero for all the demands and ports. The new values are assigned when the model is about to be solved.

o_i^m Binary parameter that is equal to 1 if *i* is the origin of demand m and 0 otherwise.

d_i^m Binary parameter that is equal to 1 if *i* is the destination of demand m and 0 otherwise.

p Time at port for a vessel in days.

n Number of spoke ports.

Cost parameters

g Fuel cost for a vessel while sailing at sea.

h Fuel cost for a vessel when staying at port.

k_i Fixed port call costs at port *i*.

q_i Variable port call costs at port *i*.

f Daily time charter rate of a vessel.

l_i Lift costs at port *i*.

Vessel parameters

e Capacity of a vessel.

$t_{i,j}$ Sailing time of a vessel on arc (i, j).

Decision Variables

x_{ij}^{mv} Quantity of demand *m* carried by a vessel *v* on arc *(i,j)*.

y_{ij}^v Binary variable that is equal to 1 if an arc *(i,j)* is sailed by a vessel *v*, 0 otherwise.

u_i^v Integer variable used for sub-tour elimination purposes.

w^v Binary variable equal to 1 if a vessel *v* is put in used, 0 otherwise.

Model and Constraints

Most of the components in the objective are similar to those in the objective in the static model, except for the time charter cost. Expressions (24), (25) and (27) account for the bunker costs, port call costs and lift cost, respectively. There are no changes in these calculations. Terms (26) illustrate that the time charter cost in the dynamic model is calculated based on the time vessels are in use, including sailing time at sea and time at visiting ports. Since there is no fixed sailing schedule, there is no restriction on sailing time. Liner shipper must pay time charter cost for the whole period that they charter in the vessels.

$$\min \sum_{v \in V} \sum_{(i,j) \in A} g t_{ij} y_{ij}^{v} + \sum_{c \in C} \sum_{v \in V} \sum_{(i,j) \in A} h p y_{ij}^{v} \tag{24}$$

$$+ \sum_{j \in P} \left(k_j + q_j e\right) \sum_{v \in V} \sum_{(i,j) \in A} y_{ij}^{v} \tag{25}$$

$$+ \sum_{v \in V} \sum_{(i,j) \in A} (t_{ij} + p) f y_{ij}^{v} \tag{26}$$

$$+ \sum_{m \in D} \sum_{v \in V} \sum_{(i,j) \in A} o_i^m l_i x_{ij}^{mv} + \sum_{m \in D} \sum_{v \in V} \sum_{(i,j) \in A} d_j^m l_j x_{ij}^{mv} \tag{27}$$

Demand constraints are comparable to those in the static model. It is required that all demands must be transported to their destination (constraints 28), no transshipment is allowed (constraints 29), and the amount shipped on a vessel must be lower than the vessel’s capacity (constraints 30).

$$\sum_{v \in V} \sum_{(i,j) \in A} x_{ij}^{mv} - \sum_{v \in V} \sum_{(j,i) \in A} x_{ji}^{mv} = \theta_i^m, \qquad i \in P, m \in D \tag{28}$$

$$\sum_{(j,i) \in A} x_{ji}^{mv} - \sum_{(i,j) \in A} x_{ij}^{mv} + \theta_i^m d_i^m \leq 0, \qquad m \in D, i \in S, v \in V \tag{29}$$

$$\sum_{m \in D} x_{ij}^{mv} \leq y_{ij}^{v} e, \qquad v \in V, (i,j) \in A \tag{30}$$

Route constraints

$$\sum_{(i,j)\in A} y_{ij}^{v} - \sum_{(j,i)\in A} y_{ji}^{v} = 0, \qquad i \in P, v \in V \tag{31}$$

$$\sum_{j\in S} y_{ij}^{v} - w^{v} \geq 0, \qquad v \in V, i \in H \tag{32}$$

$$u_i^v - u_j^v + (n+1)y_{ij}^v \leq n, \qquad v \in V, i \in S, j \in S, i \neq j \tag{33}$$

$$\sum_{j\in S} y_{ij}^{v} \leq 1, \qquad v \in V, i \in H \tag{34}$$

Constraint (31), (32) and (33) subject to the cyclic constraints, constraints regarding sailing starting point from the hubs and constraints preventing sub-tours among spoke ports, respectively. Constraints (34) require that all the demands from the hubs to be transported on the sailing day. It does not allow a vessel to visit the hub ports more than once in one service to pick up new demands; instead, the fleet size must, at least, be able to pick up all the demands at the hub at once.

The "for" loop and the dynamic part of the model

In order to generate the demand arrival schedule and also record results from the base model after each run, several parameters are needed. The new parameters are categorized into two groups, i.e. dynamic parameters and report parameters.

Dynamic parameters

The dynamic group consists of parameters concerning the demand arrival and demand volume in the network with a time dimension and the parameter for the trigger value.

t_{max} Planning horizon.

a^m Integer parameter which receives value from 1 to t_{max} based on the uniform distribution, which assigns the arrival day for each demand *m*.

c_t^m Binary parameter that is equal to 1 if the demand arrival day of demand *m* is day *t*, otherwise 0.

b_{it}^m Quantity of demand *m* that arrives at port *i* on day *t*. The parameter is positive if *i* is the origin for demand *m,* negative if *i* is the destination and 0 otherwise. The parameter concerns only the demands arriving at their origin port on day *t*.

d_{it}^m Quantity of demand *m* at port *i* on day *t*. The parameter is positive if *i* is the origin for demand *m,* negative if *i* is the destination and 0 otherwise. The parameter contains all the demands that are present in the network on day *t*, including those arriving on day *t* and those have been in the network before day *t*.

α Threshold that decides whether vessels should sail and the transport operation should take place or not.

Every time the "if" condition is satisfied, a network is created to bring the demands to their destination. The result from the base model has no time dimension; therefore, the report parameters are needed to store the result and assign it to the correct time point.

Report parameters

ζ_t Objective value of the network whose sailing day is day *t*.

μ_{tij}^{mv} Quantity of demand *m* carried by vessel *v* on arc *(i,j)* on the service which starts on day *t*.

γ_{tij}^{v} Binary parameter that is equal to 1 if an arc *(i,j)* is sailed by a vessel *v* on the service which starts on day *t,* 0 otherwise.

ϑ^t Number of vessels sailing from the hub on day *t*.

Parameter $c_t^m, b_{it}^m, d_{it}^m, \zeta_t, \mu_{tij}^{m,v}, \gamma_{tij}^v$ and ϑ^t have a default value of 0. New values will be assigned when the "for" loop starts running.

Mathematical formulation of the "for" loop and "if" condition

$$a^m = ceil\left(uniform(0, t_{max})\right) \tag{35}$$

for {*t* in 1.. t_{max}}

$$assign\ c_t^m = \begin{cases} 1\ if\ a^m = t \\ 0\ if\ a^m \neq t \end{cases} \tag{36}$$

$$assign\ b_{i,t}^m = Q^m c_t^m o_i^m - Q^m c_t^m d_i^m \tag{37}$$

$$assign\ d_{it}^m = d_{it-1}^m + b_{it}^m \tag{38}$$

If

$$\left(\sum_{m\in D}\sum_{i\in P} d_{it}^{m} \geq \alpha\right) \tag{39}$$

then

{

$$assign\ \theta_{i}^{m} = d_{it}^{m} \tag{40}$$

Solve the base model

$$assign\ \zeta_{t} = \text{Optimal Objective value} \tag{41}$$

$$assign\ \mu_{tij}^{mv} = x_{ij}^{mv} \tag{42}$$

$$assign\ \gamma_{tij}^{v} = y_{ij}^{v} \tag{43}$$

$$assign\ \vartheta^{t} = \sum_{v\in V} w^{v} \tag{44}$$

$$assign\ d_{it}^{m} = 0 \tag{45}$$

}

Equations (35) generate the arrival schedule for each demand. This information will not be incorporated in the base model; instead, it is used as a reference in the "for" loop to determine which demand will arrive on a specific day *t*. For example, if the loop is on day 1, only the information regarding day 1 in parameter a^{m} is called in in the "for" loop. The information related to day 2 to the last day of the horizon stays unknown to both the "for" loop and the base model.

The "for" loop goes through each of the days in the planning horizon. Equations (36) retrieve the information from the parameter a^{m} to decide which demand is arriving on day *t*. The parameter c_{t}^{m} receives the value of 1 if demand *m* arrives on day *t*; otherwise, zero. Equations (37) construct a matrix containing the quantity of the demands that are coming on day *t*. The expression on the right side of equations (37) ensures that b_{it}^{m} has the same formula as b_{i}^{m} (expression (1)) in the static model, i.e. if the port is the origin of the demand, the quantity is positive; if the port is the destination of the demand, the quantity has a negative sign; otherwise, the quantity is zero. The parameter c_{t}^{m} is used in equations (37) to ensure that if demand *m* does not arrive on day *t*, its quantity will remain zero for all the port. Equations (38) construct the matrix of all the demands which are available at their original port on day *t*.

The “if” condition to set off the base model is that the total available demand on day *t* is equal to or greater than the trigger α. The course of actions after the trigger is met as follows:

Equations (40) assign the value of d_{it}^{m} to parameter θ_{i}^{m}.This is where the link between the base model and the dynamic part occurs. Parameter θ_{i}^{m} has the same value as parameter d_{it}^{m}, except that the time dimension is removed. The base model does not design the network based on the total demand for the whole planning horizon, but the total demand available on day *t*.

After solving the base, static model, report parameters are used to record the result. Equations (41) - (44) assign the value of the objective value and decision variables from the base model to the report parameters, including the amount of demand shipped by vessel *v* on arc *(i,j)*, the information if vessel *v* sails on arc *(i,j)* or not and the number of vessels sailing in the network, respectively. The reporting parameters have the time dimension to mark the day when the network is designed, and the vessels start sailing.

Equations (45) set the value of the available demand on the network at the end of day *t* back to zero. This means the second time the base model is run, the demand information fed into the model is completely separated from the input information in the first run. In other words, there is no connection between the networks designed by different runs of the base model.

On the last day of the planning horizon, the “if” condition is no longer tested, instead, the base model designs a network to bring all the demand left at their original port to the destination. The body part inside “if” statement remains while the “if” test itself is removed.

5 Data description

The goal of this chapter is to describe how data for conventional and autonomous vessels is obtained. Subchapter 5.1 introduces the Liner-Lib data instances and the main sources it is based on. Subchapter 5.2 provides a comparison between the Liner-Lib benchmark suite and the cost structure of a liner shipping company described by Stopford (2009). Baltic data instances used for reporting the computational results for the purposes of the thesis are presented in subchapter 5.3. Subchapter 5.4. describes the adjustment made to the initial data instances in order to obtain parameters for the autonomous fleet. Low, basic and high demand scenarios are introduced in subchapter 5.5.

5.1 Data collection

Albeit numerous research papers had been conducted since the LSNDP got its share of attention in the operations research domain, there was no common ground to compare these models and solution methods. Each researcher had their own perspective on various liner shipping costs and decisive restrictions in the network. Brouer et al. (2014a) introduce the Liner-Lib benchmark suite with the ambition that “The benchmark suite is seen as the root of a tree where new branches will appear as our ability to solve more complex interpretations of the liner shipping problem grows”.

The benchmark suite is created based on the historical data from Maersk Line and publicly available sources, including National Imagery and Mapping Agency (2011); Vereinigung Hamburger Schiffsmakler und Schiffsagenten (2011); Alphaliner (2010); Drewry Shipping Consultants (2010).

The suite has seven data instances, each of them consisting of four lists, i.e. distance list, demand list, fleet list and port list. The costs and revenue in all the instances are not representing those of any liner shipping company but, instead, the relative cost structure in the global liner shipping business. The authors try to replicate as much as possible the real cost dynamics in the international liner shipping environment. For example, in comparison with a small, distant port, a large, central port has a lower port call fee, and a container can be shipped to the latter at a lower freight rate. Besides that, in general, the cost of transshipment in Europe and North America is higher than that in Asia.

The information in the port list and the distance list is mainly captured from the real geographical data, with minimal adjustment from the authors' perspective. The costs associated with a specific port are based on the port location and size. The relation between these three factors is inferred from Maersk Line data. In the fleet list, the vessel classes are created based on the information of Maersk Line's vessel fleet. Depending on the scope of demand in the network, a particular fleet is assigned for each instance. The time charter rate is constructed based on the Hamburg index (Vereinigung Hamburger Schiffsmakler und Schiffsagenten, 2011) and the Alphaliner charter rates (Alphaliner, 2010) for vessels up to 4,800 TEU. For vessels with higher TEU, the data from Maersk Line is used to calculate the TC rates. The bunker consumption for each vessel class is computed using the well-known cubic function from Stopford (2009) and Alderton (2005).

$$F(s) = \left(\frac{s}{v_*^F}\right)^3 f_*^F \tag{46}$$

Where $F(s)$ is the bunker consumption for speed s, v_*^F is the design speed and f_*^F is the fuel consumption at the design speed.

The demand data is realistic and reflects the asymmetry, which is one of the main features of the world trade. The revenues are drawn from the Container Freight Rate Insight (Drewry Shipping Consultants, 2010) and set to 70% of the market freight rates. The transit time is constructed as 1.3 times of Maersk Line's shortest transit time in 2010.

According to Brouer et al. (2014a), the benchmark suite aims to provide comprehensive, reliable, realistic data for testing the quality of new models and methods, giving a common ground for the development of new algorithms in the context of the LSNDP. In this thesis, an adjustment to the data is made in order to extend the benchmark suite Liner-Lib to autonomous vessels. Various papers are reviewed to assess potential economic effects of the introduction of autonomous ships, i.e. Kretschmann et al. (2017), Danish Maritime Authority (2016), Hogg and Ghosh (2016). Based on these articles, in subchapter 5.4, adjustments to the fuel consumption and the operation costs are made, but first, the benchmark suite cost structure is compared with the maritime economics theory from Stopford (2009).

5.2 Cost structure – Maritime economics theory and Liner-Lib benchmark suite

Brouer et al. (2014a) simply divide the liner shipping cost structure into two main groups, that is *Fleet costs* and *Cargo-handling costs.* The authors omit administrative costs, which is reasonable due to the difference among liner shipping companies in terms of organizational structure, business model, asset portfolio and so on.

The fleet costs consist of bunker cost, capital cost, port call cost, canal cost and operational cost. Brouer et al. (2014a) use the time charter rate to represent the capital costs and operating costs with the argument that time charter rate is the market price at which shipowners can charter out their ships when the supply of vessels is higher than the demand for oversea transportation. Bunker cost takes into account both the sailing time and the time at port with different fuel consumption rates. Port costs include a fixed fee per port call and a variable cost depending on capacity. Canal cost, which ships must pay if their routes have canals involved, is also mentioned in the data. Canal cost is not one of the primary costs that carriers must pay for all of its services; however, the cost itself is not inconsiderable, and many liner carriers do sail through canals in the effort to cut down their sailing time. In general, the fleet cost structure employed by Brouer et al. (2014a) covers all the costs related to ships and port charges that are discussed and analyzed by Stopford (2009). The authors also include canal cost, which is non-trivial when designing extensive networks covering more than one continent.

In their benchmark suite, Brouer et al. (2014a) include lift cost for loading and discharging containers at port and transshipment cost in the cargo-handling cost group, which are directly affected by the demand and the choice of services in the network. Loading/unloading cost and transshipment cost are applied for both empty and full containers at the same rate. All the containers are considered as identical, and there are no different treatments or costs related to a specific type of container among them. Some other costs, like capital cost, maintenance and repair cost, and interzone repositioning cost for containers, which are discussed in Stopford (2009), are not included in the data. Although Brouer et al. (2014a) use multiple arguments, findings and conclusions from Stopford (2009) in the paper, the authors do not explain the reason for partially omitting container costs from their model.

Compared to the liner cost analysis from Stopford (2009), Brouer et al. (2014a) provide a clear and more straightforward cost structure with a majority of actual and relevant costs for the LSNDP, which creates a good ground for other researchers to develop new algorithms and model to solve the problem. It can be said that the focus of the benchmark suite is on the LSNDP, and removing irrelevant costs is necessary to ensure the solvability of the problem.

5.3 Baltic Data instances

Liner-Lib contains seven data instances of different size such as single-hub instances Baltic and West Africa, Mediterranean multi-hub instances, trade lane instances Pacific and AsiaEurope and Small and Large world instances. The smallest data set is Baltic with 12 ports and 22 demands, and the largest one is Large world with 197 ports and 9,630 demands (Brouer et al., 2014). For the purposes of this thesis, the Baltic data instances are used to report the computational results.

Figure 5. Baltic instances (Brouer et. al, 2014a)

The Baltic instances include 12 ports situated in seven countries and named according to the UN/LOCODE scheme: Bremerhaven, Germany (DEBRV); Aarhus, Denmark (DKAAR); Finnish ports Kotka (FIKTK) and Rauma (FIRAU); Norwegian ports Aalesund (NOAES), Bergen (NOBGO), Kristiansand (NOKRS) and Stavanger (NOSVG); Gdynia, Poland (PLGDY); Russian ports Kaliningrad (RUKGD) and Saint Petersburg (RULED); and Goteborg, Sweden (SEGOT). Some of these ports have access to the Baltic Sea, and some of them are situated on the North Sea. Figure 5 shows the positioning of these ports on the map.

Fleet in the Baltic instances consists of four feeders with the capacity of 450 FFE and two feeders with the capacity of 800 FFE, their design speed is 12 and 14 knots, and they consume 18.8 and 23.7 tons of bunker per day at design speed and 2.4 and 2.5 tons per day when idle, respectively. The sailing time between the ports for each vessel class is calculated as distance divided by sailing speed. The sailing time is presented in Appendix D.

Liner-Lib also provides cost parameters, such as fixed and variable port call costs and lifting costs displayed in Appendix E. Bunker costs are calculated as a daily vessel consumption multiplied by the flat bunker price of USD 600 per ton used by Brouer et al. (2014a). Therefore, the bunker costs per day for feeders of 450 FFE are USD 11,280 at sea and USD 1,440 when idle. The bunker costs for feeders of 800 FFE are USD 14,220 and USD 1,500 at sea and at port, respectively. The time charter rate per day is USD 5,000 for the smaller feeders and USD 8,000 for the bigger feeders.

5.4 Data adjustments

The data instances presented by Brouer et al. (2014a) are adjusted in order to obtain parameters for autonomous vessels. Economic effects of the introduction of autonomous vessels are considered by various researchers. While different authors agree on lower crew costs, they all analyze it in a trade-off with a cost increase due to other factors such as higher construction cost of newbuildings (Danish Maritime Authority, 2016) and higher costs at the shore control center and at ports (Hogg and Gosh, 2016; Kretschmann et al., 2017).

Table 2. Considered cost changes (Kretschmann et al., 2017)

Operating costs	Voyage costs
Crew wages (–)	Air resistance (–)
Crew related costs (–)	Light ship weight (–)
Shore control center (+)	Hotel system(–)
Maintenance crews (+)	Boarding crew for port calls (+)

Kretschmann et al. (2017) consider changes in operating, voyage and capital costs for autonomous vessels compared to the conventional ones. The summary of the operating and voyage costs changes is presented in Table 2.

A cost saving potential lays in crew wages and crew related costs which include salaries and all living expenses of the crew such as hotel system, medical expenses and safety equipment. Based on Kretschmann et al. (2017), the share of crew wages in total operational costs is 45%, and the share of stores costs that will be eliminated in autonomous vessels is 3%; therefore, *the operational costs* are reduced by 48%. For the feeders of 450 FFE the operational costs are reduced by USD 2,400, and amount to USD 2,600 per day, and for the feeder of 800 FFE they are reduced by USD 3,840 and amount to USD 4,160 per day.

The shore control center and maintenance crew costs are ignored for the purpose of the thesis as it is difficult to estimate the amount as of today. A shore control center will be able to monitor a large number of vessels, i.e. the MUNIN project considers a shore control center that is responsible for 90 vessels at a time (MUNIN, 2015). To the authors' knowledge, there is no literature that considers how the shore control center and maintenance crew costs should be calculated, and it is out of the scope of the thesis to estimate them. Therefore, these costs are not included in the calculation.

Decrease of voyage costs of autonomous vessels is driven by reduced air resistance, lighter ship weight and lower electricity consumption associated with the hotel system (Kretschmann et al., 2017). These factors, in their turn, contribute to the reduction of auxiliary engine fuel consumption. Different estimates of the fuel consumption reduction rate are presented in the literature. For the purpose of this thesis, the *fuel consumption* is reduced by 6 % (Kretschmann et al.) and comprises 17.7 tons per day for the feeder of 450 FFE when sailing at sea. For the feeder of 800 FFE, the fuel consumption is reduced to 22.3 tons per day when at sea. The decrease of 6% used in the thesis is a conservative estimate as other researches claim that the potential reduction can be between 12% and 15% (Arnsdorf, 2014).

As the Liner-Lib benchmark suite does not contain information for feeders with a lower capacity than 450 FFE, the data instances are extended to the vessels of 200 FFE ensuring consistency with both the benchmark suite and the reality. The *design speed* of these feeders is assumed to be 11 knots which is slightly lower than the design speed of bigger feeders and is in line with existing vessels of similar size (FleetMon, 2020). *Fuel consumption at sea* is found using multiple linear regression with explanatory variables capacity, and design speed based on the whole fleet provided by Brouer et al. (2014a) which is presented in Appendix F. The value obtained after running regression is fuel consumption for a conventional vessel of 200 FFE. The value is reduced by 6% to show the savings caused by a higher efficiency of autonomous ships (Kretschmann et al., 2017). Calculation details are presented in Table 3.

Table 3. Calculation of fuel consumption at sea for autonomous vessels of 200 FFE

Description	**Value**
Adjusted R Square	0.992
a (intercept)	-41.728
b_1(capacity)	0.013
b_2(design speed)	4.293
Fuel consumption at sea for a conventional vessel, tons per day	8.033
Fuel consumption at sea for an autonomous vessel, tons per day	7.551

Fuel consumption when idle changes only slightly with the vessel size. As daily *time charter rate* fluctuates significantly with the market and depends on the date when it is obtained, it is calculated for vessel class 200 FFE using linear regression over the capacity based on the whole fleet (Appendix F). In order to get the TC rate for autonomous vessels, the obtained value is reduced by 48% due to operating costs savings described above, i.e. reduction of wages and stores costs (Kretschmann et al., 2017). Calculation details of daily time charter rate are presented in Table 4.

Table 4. Calculation of daily TC rate for autonomous vessels of 200 FFE

Description	**Value**
Adjusted R Square	0.994
a (intercept)	2,781.102
b_1(capacity)	7.149
Daily TC rate for a conventional vessel	4,210.871
Daily TC rate for an autonomous vessel	2,189.653

However, as there is no crew on board while sailing at open sea, approaching and berthing require hiring a boarding crew at ports. Such a service might be offered by ports where local workers facilitate approaching and berthing of autonomous ships. This leads to an increase in *port call costs* by 20% (Kretschmann, 2017). The adjusted fixed port call costs are presented in Appendix E.

The summary of the parameters for conventional and autonomous vessels according to their size is presented in Table 5.

Table 5. Parameters for conventional and autonomous vessels according to their size

Parameters	**Conventional vessels**		**Autonomous vessels**		
Capacity, FFE	450	800	200	450	800
Design speed, knots	12	14	11	12	14
Fuel consumption at sea, tons/day	18.8	23.7	7.6	17.7	22.3
Fuel consumption when idle, tons/day	2.4	2.5	2.3	2.4	2.5
Daily TC rate, USD	5,000	8,000	2,190	2,600	4,160

Regarding *time at port*, Brouer et al. (2014a) applied 24-hours port time for all vessels, which includes both feeders and trans-ocean container ships. In the example of the eight building-blocks of liner costs, Stopford (2009) estimated that the port time for a vessel of 1,200 TEU is 0.7 days. Even though there is no linear relationship between the vessel size and time spent at port, it is reasonable to assume that smaller vessels use less time per port call than much larger vessels. Since the fleet employed in the Baltic instance involves only feeders with the maximum capacity of 800 FFE, the port time is estimated to be approximately 0.5 days, for both regular and autonomous vessel.

5.5 Demand scenarios for Baltic data instances

In order to explore how the optimal solutions are affected by changes in demand, low, basic and high demand scenarios are introduced. The realistic demand data provided by Brouer (2014) is taken as *the basic scenario*. In *the high demand scenario*, the demand volumes are increased by 15%. As considered in the report on the future of shipping in the Baltic Sea for the Baltic LINes project (Matczak, 2018), in the fast growth scenario Baltic shipping volume will yield an increase by 12% until 2030 driven by all countries in the region, population growth and enrichment and technological innovations. According to a forecast provided by ISL Institute of Shipping Economics and Logistics (2014), the volumes will grow by 22% by 2030. Therefore, an increase of 15% is considered reasonable. *The low demand scenario* represents a decrease of 10%. The ISL (2014) explained the 10% decrease by the effects of stricter regulations in Sulfur Emission Control Areas after January 1st, 2015. Moreover, the decrease might be driven by the impact of

COVID-19 on the shipping industry, as it might have profound and long-term effects on the global trade (Condon et al., 2020).

6 Computational study

In this chapter, the results of the computational study are presented. Subchapter 6.1 shows the model performance on the Baltic data instances. Subchapter 6.2 presents costs, route structures, capacity utilization and lead time for different fleets in basic, low and high demand scenarios.

6.1 Model performance

The models are implemented in the modelling tool AMPL using Gurobi Optimizer version 9.0.2. The experiments are run on an AMD Ryzen 5 2600X six-core processor with 3.60GHz.

Table 6. Test results for the normal scenario

Fleet configuration	Time, hours	Gap, %	Objective, th'USD
Regular fleet (450 FFE and 800 FFE)	1	5.75	3,787
	2	5.33	3,787
	3	5.05	3,787
	4	4.88	3,787
	5	4.72	3,787
Autonomous fleet (450 FFE and 800 FFE)	1	3.51	3,664
	2	3.02	3,664
	3	2.84	3,664
	4	2.77	3,664
	5	2.71	3,664
Autonomous fleet (200 FFE and 450 FFE)	1	7.82	3,735
	2	6.96	3,735
	3	6.96	3,735
	4	6.96	3,735
	5	6.96	3,735
Autonomous fleet (200 FFE and 800 FFE)	1	8.02	3,531
	2	6.21	3,517
	3	5.83	3,517
	4	5.61	3,517
	5	5.57	3,517
Autonomous fleet (200 FFE)	1	11.00	4,081
	2	8.66	4,021
	3	8.45	4,021
	4	8.45	4,021
	5	8.45	4,021

For the purposes of the thesis the analyses are performed on five different fleet configurations such as a fleet of regular vessels with a capacity of 450 FFE and 800 FFE, a fleet of autonomous vessels with the same capacity as the regular vessels, a fleet of autonomous vessels with a capacity of 200

FFE, and two combined fleets: with vessels of 200 FFE and 450 FFE; and with vessels of 200 FFE and 800 FFE for the static model. The dynamic model is solved for the fleet of autonomous vessels of 200 FFE. All these instances are tested under low, basic and high demand scenarios.

In order to choose the time limit for the Gurobi solver to run all data instances under all the scenarios, they are firstly solved under the basic scenario within different time limits, i.e. one, two, three, four and five hours. The results are presented in Table 6, where the first column reports the fleet configuration, and the second column reports the running time for the solver. The third column shows the optimality gap, i.e. the gap between the best feasible solution and the best known lower bound. The third column reports the objective value when the algorithm terminates.

From the results reported in Table 6, it can be seen that the gap changed significantly when the time increased from one to two hours, the objective also decreases for some of the instances after two hours. After two hours, the best feasible solution remains the same in most of the cases, and the gap decreases only slightly, which can also be seen in Figure 6. Therefore, the time limit for the low and high scenarios for the static model and all scenarios for the dynamic model is chosen as two hours.

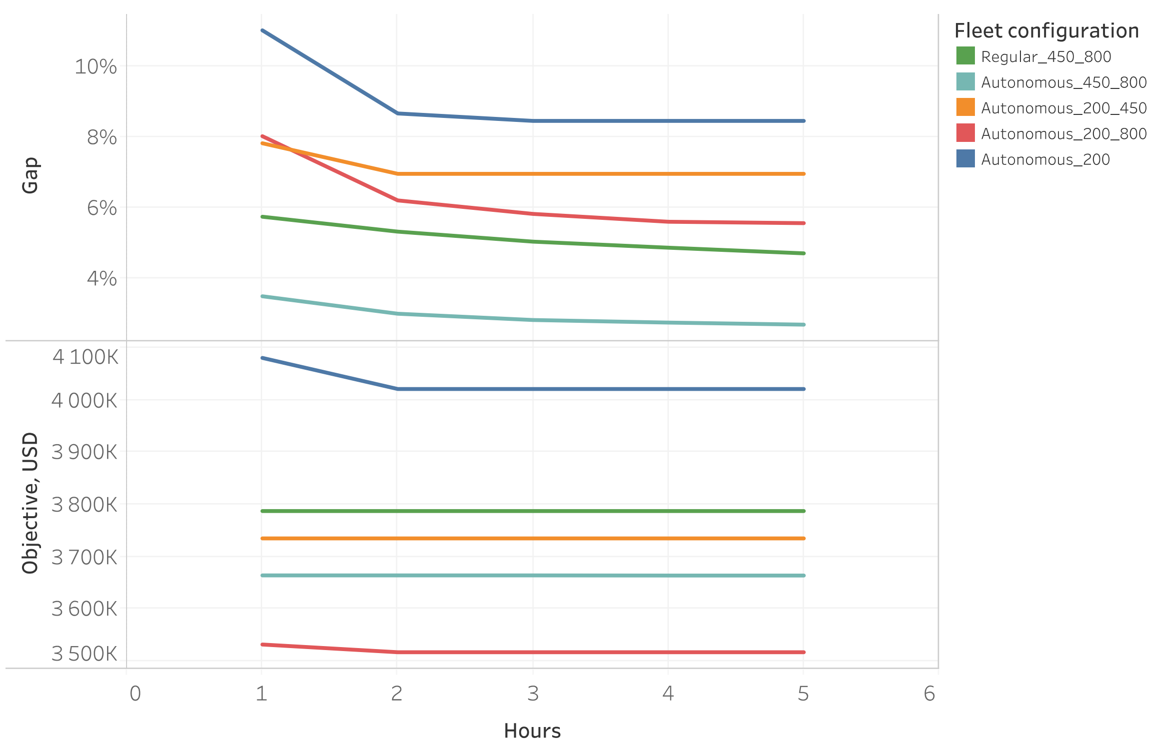

Figure 6. Test results for the normal demand scenario

The model is tested with a much longer running time; however, after five hours, the gap decreases only 0.01% every couple of hours with a diminishing speed. The experiments cannot be solved to the absolute optimality due to the enormous number of variables and a lack of computing power. In the basic scenario, the static model with the fleet of 800-FFE and 450-FFE vessels consists of 17,424 continuous variables and 1,658 integer variables after presolving. These two numbers are 31,944 and 3,038 for the fleet of 800-FFE and 200-FFE vessels, 34,848 and 3,312 for the fleet of 450-FFE and 200-FFE vessels, and finally 49,368 and 4,692 for the fleet of only 200-FFE vessels.

In order to verify the reliability of the result from the experiments above, a smaller sample derived from the Baltic sea instance is implemented in the model and solved to the absolute optimality. The small instance includes seven ports, i.e. Bremerhaven, Germany (DEBRV); Rauma, Finnish (FIRAU); Norwegian ports Aalesund (NOAES) and Stavanger (NOSVG); Gdynia, Poland (PLGDY); Saint Petersburg, Russia (RULED); and Goteborg, Sweden (SEGOT). The new network has a similar structure as the original one as the three farthest spoke ports remain, and each country maintains at least one representative port, except for Denmark. A brief discussion of the optimal result from the small instance is presented at the end of subchapter 6.2 to verify the outcome from the run with the original instance.

6.2 Results

The experiment compares the result from the LSNDP with a fleet of conventional vessels of 450 and 800 FFE and fleets of autonomous vessels of 450 and 800 FFE, 200 and 450 FFE, 200 and 800 FFE, 200 FFE for low, basic and high demand scenarios, using the static model and the dynamic model. The objectives are (i) to study economic effects of introducing autonomous vessels into the liner shipping network, (ii) to analyse which fleet configuration leads to lower operational costs, and (iii) to explore how a dynamic sailing schedule for autonomous vessels affects the total cost and service level of the network.

6.2.1 Effects of autonomous vessels introduction into the liner shipping network

To answer the first questions, six experiments are conducted in three scenarios using the static model with two datasets, regular and autonomous fleets with vessels of 450 and 800 FFE. The results are presented in Tables 7 - 9. Each table includes profit, revenue and total costs broken down into bunker costs, port call costs and time charter costs for each class of vessel and lifting costs.

Table 7. Results of LSNDP for the basic scenario, in th'USD

Fleet configuration	Profit	Revenue	Total cost	Bunker cost	Port call cost	Time charter costs	Lifting cost
Regular (450 and 800 FFE), incl.:	267	4,055	3,787	422	758	294	2,313
Feeders of 450 FFE				*113*	*376*	*70*	
Feeders of 800 FFE				*309*	*382*	*224*	
Autonomous (450 and 800 FFE), incl.:	391	4,055	3,664	398	800	153	2,313
Feeders of 450 FFE				*107*	*396*	*36*	
Feeders of 800 FFE				*291*	*404*	*116*	
Autonomous (200 and 450 FFE), incl.:	368	4,055	3,687	506	694	173	2,313
Feeders of 200 FFE				*76*	*258*	*46*	
Feeders of 450 FFE				*430*	*436*	*127*	
Autonomous (200 and 800 FFE), incl.:	538	4,055	3,517	353	688	162	2,313
Feeders of 200 FFE				*76*	*258*	*46*	
Feeders of 800 FFE				*276*	*430*	*116*	
Autonomous (200 FFE)	33	4,055	4,021	528	874	307	2,313

Table 8. Results of LSNDP for the low scenario, in th'USD

Fleet configuration	Profit	Revenue	Total cost	Bunker cost	Port call cost	Time charter costs	Lifting cost
Regular (450 and 800 FFE), incl.:	125	3,649	3,524	425	723	294	2,082
Feeders of 450 FFE				*127*	*438*	*70*	
Feeders of 800 FFE				*298*	*284*	*224*	
Autonomous (450 and 800 FFE), incl.:	249	3,649	3,400	400	765	153	2,082
Feeders of 450 FFE				*120*	*462*	*36*	
Feeders of 800 FFE				*281*	*303*	*116*	
Autonomous (200 and 450 FFE), incl.:	279	3,649	3,370	479	651	158	2,082
Feeders of 200 FFE				*53*	*233*	*31*	
Feeders of 450 FFE				*426*	*418*	*127*	
Autonomous (200 and 800 FFE), incl.:	427	3,649	3,222	330	663	147	2,082
Feeders of 200 FFE				*53*	*233*	*31*	
Feeders of 800 FFE				*276*	*430*	*116*	
Autonomous (200 FFE)	11	3,649	3,638	480	800	276	2,082

Table 9. Results of LSNDP for the high scenario, in th'USD

Fleet configuration	Profit	Revenue	Total cost	Bunker cost	Port call cost	Time charter costs	Lifting cost
Regular (450 and 800 FFE), incl.:	432	4,663	4,231	519	730	322	2,660
Feeders of 450 FFE				*363*	*587*	*210*	
Feeders of 800 FFE				*156*	*143*	*112*	
Autonomous (450 and 800 FFE), incl.:	496	4,663	4,167	519	799	189	2,660
Feeders of 450 FFE				*226*	*538*	*73*	
Feeders of 800 FFE				*292*	*260*	*116*	
Autonomous (200 and 450 FFE), incl.:	497	4,663	4,166	569	729	207	2,660
Feeders of 200 FFE				*104*	*266*	*61*	
Feeders of 450 FFE				*465*	*463*	*146*	
Autonomous (200 and 800 FFE), incl.:	649	4,663	4,013	441	703	208	2,660
Feeders of 200 FFE				*159*	*412*	*92*	
Feeders of 800 FFE				*282*	*292*	*116*	
Autonomous (200 FFE)	141	4,663	4,522	593	931	337	2,660

In all the scenarios, the introduction of autonomous vessels leads to a decrease of total costs and, as a result, to an increase of profit due to a reduction of time charter costs and bunker costs compensated by higher port call costs. When switching from the regular fleet to the autonomous fleet, the total costs reduce by 3% in the basic demand scenario and by 4% and 2% for the low and the high demand scenarios, respectively. The lifting costs remain the same for all fleet configurations in each demand scenario. The main contribution to the total operating costs reduction is made by the time charter costs due to the lower wages and storage expenses; they reduce by around 40% in all the scenarios. In the low and basic scenarios, bunker costs for autonomous ships are 6% lower, which also contributes to the cost savings. However, in the high demand scenario, the fuel costs do not change for the autonomous fleet compared to the conventional fleet.

6.2.2 Comparison of autonomous fleet configurations

To compare the performance among different fleet configurations, experiments are conducted for four autonomous fleets, i.e. with the capacity of 450 and 800 FFE, 200 and 450 FFE, 200 and 800 FFE, and 200 FFE, in three demand scenarios under the static model. The results are presented in Tables 7 - 9.

Fleet configuration has an impact on the total costs and the route structure as vessels of different sizes may be used on routes with different length and demand volume. In the Baltic trade case, the lowest costs are achieved by the fleet of autonomous vessels of capacity 200 and 800 FFE while the highest costs incur in the network with autonomous vessels of 200 FFE for all demand scenarios. The fleet of 200 and 800 FFE in all cases attains the lowest bunker costs; however, the time charter costs in the basic and high scenarios are lower for the fleet of 450 and 800 FFE by 6% and 9%, respectively. This is explained by the fact that in the low scenario when the demand decreased by 10%, the fleet with smaller vessels allows ceasing the usage of one of the vessels with a capacity of 200 FFE which contributes to savings on time charter costs. In the basic and high scenarios, on the other hand, having bigger vessels in the fleet allows using fewer of them. The port call costs are 2% lower for the fleet of 200 and 450 FFE in the low scenario due to variable port costs increase when using vessels of 800 FFE.

The fleet with vessels of 200 FFE leads to the highest operating costs which are greater than the operating costs of the best performing fleet by 14% in the basic scenario and 13% in the low and high scenario. The highest growth is related to the time charter costs (by 62 - 89% through different scenarios) and bunker costs (by 34 - 50% through different scenarios) which is due to a large increase in the number of vessels needed in order to transport all the demands in the network.

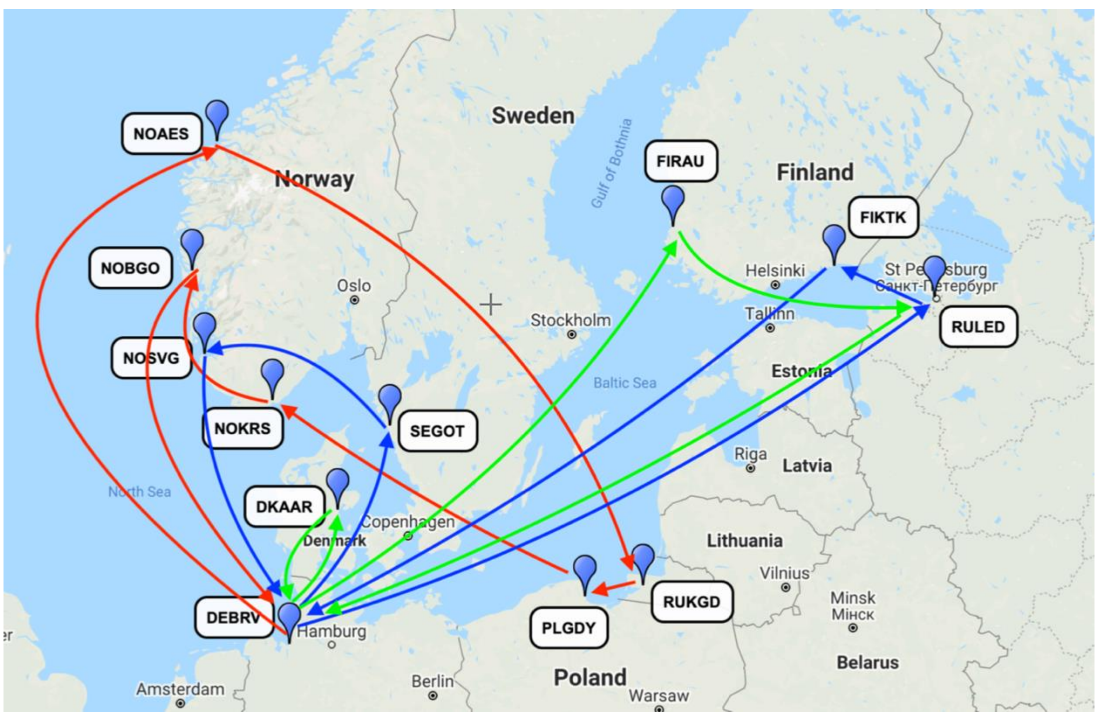

Figure 7. Route structures generated for the regular fleet (450 and 800 FFE)

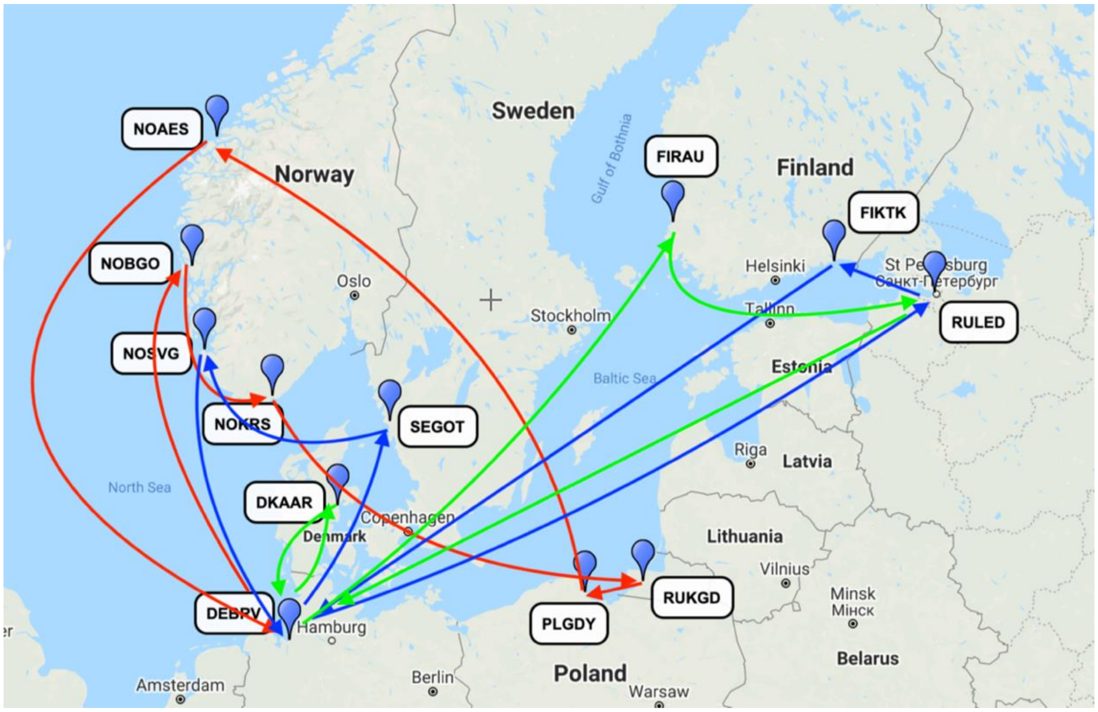

Figure 8. Route structures generated for the autonomous fleet (450 and 800 FFE)

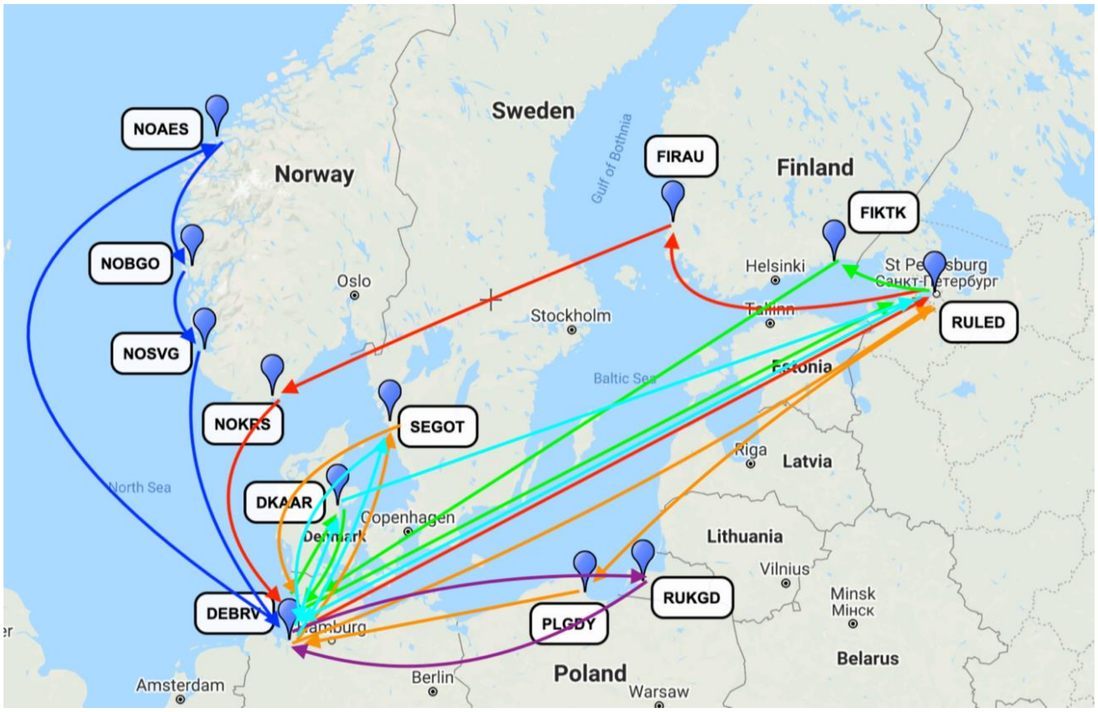

Figure 9. Route structures generated for the autonomous fleet (200 and 450 FFE)

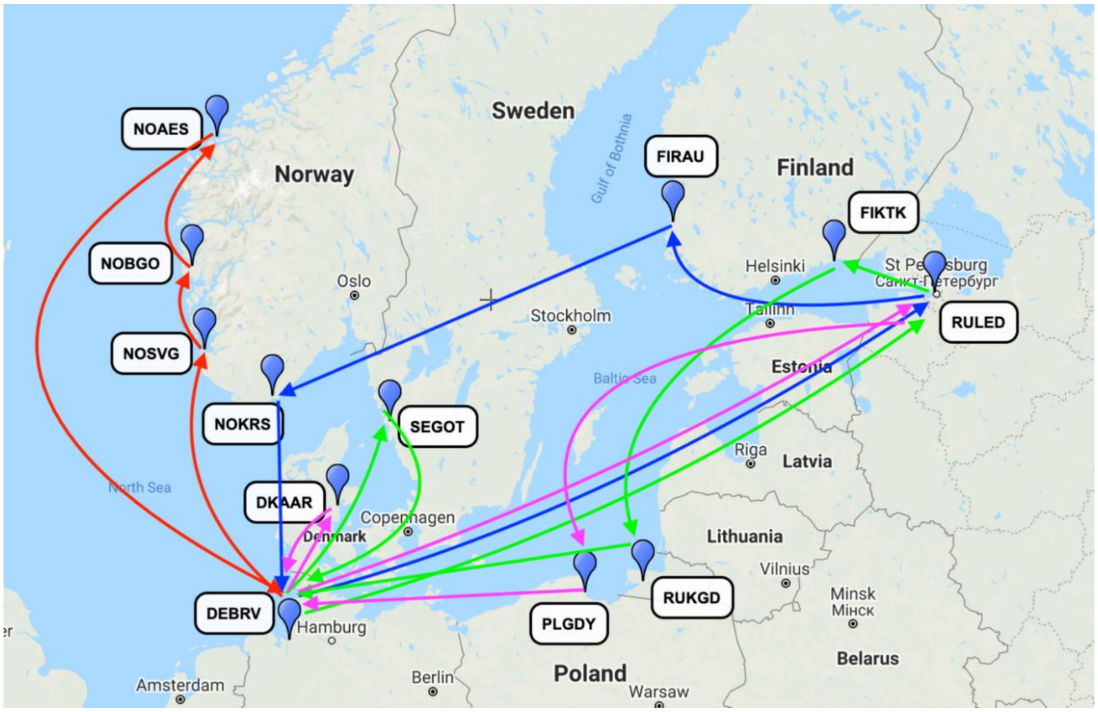

Figure 10. Route structures generated for the autonomous fleet (200 and 800 FFE)

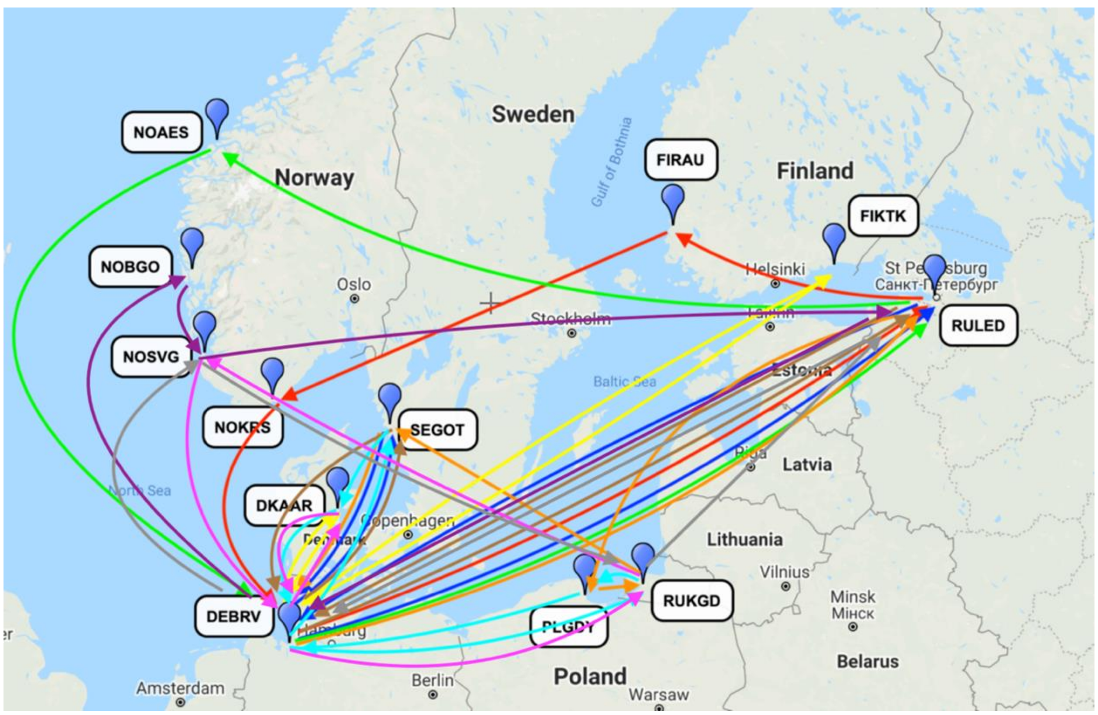

Figure 11. Route structures generated for the autonomous fleet (200 FFE)

The routes constructed by the LSNDP for the basic demand scenario are presented in Figures 7 - 11. The services for all demand scenarios with the fixed schedule are reported in Appendix G. The figures show both simple and butterfly route structures for all fleet configurations. The routes for the fleets with regular and autonomous vessels of 450 and 800 FFE are almost identical, which is rational. As mentioned in subchapter 5.3, the Baltic data instances, just like the world trade, has an asymmetric nature with high demand from Bremerhaven (DEBRV) to Saint Petersburg (RULED) and low demand on the back-haul leg. Moreover, the demands between ports in Norway (NOBGO, NOSVG, NOKRS) and the hub (DEBRV) are low while the distances are short. This fact explains why the fleet of 200 and 800 FFE has performed the best among the autonomous fleets as the smallest feeders are used in order to sail the Norwegian ports with low demands that could fit in the vessel and the biggest feeders are used to sail the destinations with higher demands such as Saint Petersburg (RULED), Aarhus (DKAAR) or Goteborg (SEGOT). The autonomous fleet with ships of 200 FFE, on the other hand, incurs high costs as it has to employ many small vessels in order to satisfy the demand in the farthest port, Saint Petersburg (RULED).

In Stopford (2009), capacity utilization is also one of the cost blocks that will influence the total costs of the liner shipping business. In this thesis, the capacity utilization of a vessel is calculated as an average fill-up rate of all the legs on which the vessel sails. The capacity utilization of each vessel class and each fleet is the average capacity utilization of all the vessels in the class and the fleet, respectively. The result of capacity utilization in Table 10 gives an idea of how well the fleets' capacity fits in the network. It is shown that the problem of overcapacity is not exceptionally severe. Although it is not possible to reach the capacity utilization of 100%, a high excess of capacity means an unnecessarily high cost and low profitability.

Table 10. Results of LSNDP for capacity utilization under the fixed schedule

Fleet configuration	**Average capacity utilization rate**		
	Low scenario	**Basic scenario**	**High scenario**
Autonomous 450_800, incl.:	64 %	71 %	65 %
Feeders of 450 FFE	*61 %*	*76 %*	*65 %*
Feeders of 800 FFE	*65 %*	*68 %*	*64 %*
Autonomous 200_450, incl.:	61 %	67 %	72 %
Feeders of 200 FFE	*76 %*	*76 %*	*86 %*
Feeders of 450 FFE	*57 %*	*63 %*	*64 %*
Autonomous 200_800, incl.:	66 %	64 %	72 %
Feeders of 200 FFE	*76 %*	*67 %*	*71 %*
Feeders of 800 FFE	*62 %*	*62 %*	*73 %*
Autonomous 200	68 %	73 %	71 %

The result of the capacity utilization shows two different behaviors among the four fleets. The utilization rate of the fleet of 450 and 800 FFE vessels and the fleet of 200 FFE vessels increases when the scenario changes from low to basic but then decreases when switching to the high scenario. The reason for that is the size of the fleet. In the basic and low scenario, the fleet size of these two configurations remains the same, that is, one vessel of 450 FFE and two vessels of 800 FFE for the former fleet and ten vessels of 200 FFE for the latter fleet. With a constant fleet capacity, when the demand increases from the low case to the basic case, the utilization rate rises. When the high scenario is applied, the fleet from the basic situation is not sufficient to satisfy the demand. One vessel of 450 FFE and two vessels of 200 FFE are added to the former and latter fleet, respectively. These extra fleet raises the capacity of the fleet significantly, which results in a decrease in the utilization rate. On the contrary, the fleet of vessels of 200 and 450 FFE and the fleet of 200 and 800 FFE experience an increase in the fill-up rate when changing from the low scenario to the high scenario. Whenever the demand increases, one more vessel of 200 FFE is added to the fleets to adjust to the new demand quantity. The additional capacity of 400 FFE from the low scenario to the high scenario is low, compared to the rise of the demand of 1,226 FFE, which leads to an increase in the utilization rate.

The fleet of autonomous vessels of 200 FFE always has the highest or the second-highest utilization rate since it seems to be easier to fill up small vessels. Despite that, the fleet of only 200 FFE vessels has the highest operating cost, compared to the other fleets due to the considerable number of vessels employed to satisfy the demand constraints. While the other fleets use from three to six container ships to serve the network, this number for the fleet of ships of 200 FFE is ten ships in the low and basic scenario and 12 ships in the high scenario.

The fleet of vessels of 200 and 800 FFE capacity, which has the lowest operating costs in all the three scenarios, has a high capacity utilization rate in both the low and high scenario, but the lowest utilization rate in the basic scenario. When the scenario changes from low to basic, the increase in the demand requires the liners to charter in one vessel of 200 FFE, which turns out to be operated at only 44% fill-up rate. The low utilization of the new vessel drives down the average fill-up rate of the fleet. However, the decrease is only 2%, which is also the case for the fleet of 200 FFE vessels, compared to the drop of 6% for the fleet of 450 and 800 FFE vessels when the scenario changes from basic to high. It seems that the inclusion of ships of 200 FFE in the fleet combination allows the liner to adjust the capacity of the fleet in a more flexible way, which helps to avoid a sudden increase or decrease in the fleet size and operating costs associated with it.

6.2.3 Effects of dynamic scheduling for autonomous vessels

In order to answer the third research question, the fleet of 200 FFE vessels is employed in the dynamic model, and its result is compared with the result of the static model using the same fleet configuration. The use of vessels of 200 FFE capacity emphasizes the idea of small autonomous vessels sailing in convoy following a dynamic schedule, suggested by Christiansen et al. (2019). Moreover, the fact that the Baltic instance demonstrates a small network, with some demands containing only a few containers, is also a relevant factor in this decision.

The trigger value is equal to 75% of the capacity of a basic fleet which includes ten vessels of 200 FFE. In the high scenario, more vessels are allowed to be chartered in to fulfil the demand requirement, but the trigger value is still based on the basic fleet. The choice of the trigger's value is based on the result of the fleet of 200 FFE vessels in the static model under the basic scenario, which requires ten vessels to satisfy all the demand requirement. The trigger is chosen carefully; however, it is out of the scope of this thesis to conduct an elaborate study to pick up the best trigger.

Table 11. Results of LSNDP under fixed schedule and dynamic schedule, in th'USD

Schedule types	**Profit**	**Revenue**	**Total cost**	**Bunker cost**	**Port call cost**	**Time charter**	**Lifting cost**	**Average capacity utilization rate**
Low scenario								
Fixed schedule	11	3,649	3,638	480	800	276	2,082	68 %
Dynamic schedule	-573	3,649	4,222	606	1,202	332	2,082	52%
Changes	*-5,387%*	*0%*	*16%*	*26%*	*50%*	*20%*	*0%*	*-23%*
Basic scenario								
Fixed schedule	33	4,055	4,021	528	874	307	2,313	73 %
Dynamic schedule	-514	4,055	4,569	650	1,249	356	2,314	54%
Changes	*-1,646%*	*0%*	*14%*	*23%*	*43%*	*16%*	*0%*	*-27 %*
High scenario								
Fixed schedule	141	4,663	4,522	593	931	337	2,660	71 %
Dynamic schedule	-497	4,663	5,160	746	1,347	406	2,661	56 %
Changes	*-452%*	*0%*	*14%*	*26%*	*45%*	*20%*	*0%*	*-21 %*

Table 11 illustrates a comparison between the results of sailing a fleet of only 200 FFE vessels under a fixed schedule and flexible schedule in the three scenarios.

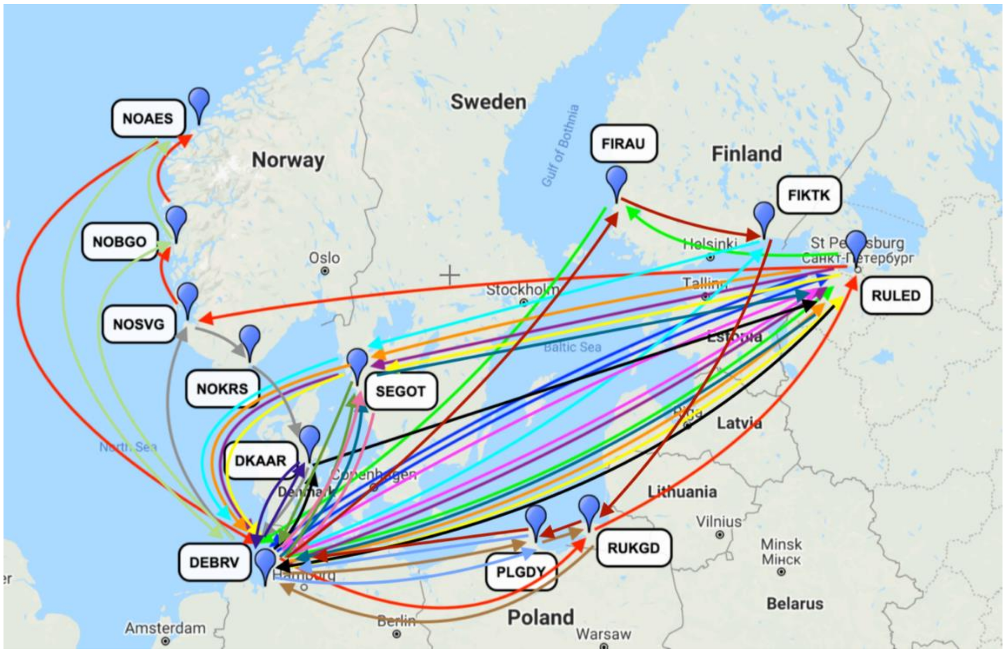

Figure 12. Route structures generated by the LSNDP with dynamic schedule

The services for all demand scenarios with the flexible schedule are reported in Appendix H. The result indicates that the fixed schedule outperforms the flexible schedule in both cost and capacity utilization aspects. Applying the flexible sailing schedule with the trigger for the action of sailing is 75% of the basic fleet capacity leads to a loss on the side of liner shipping companies. The bunker cost and the port call cost rise substantially as more port visits have been made and more vessels sail on the same legs under the dynamic schedule. For example, in the fixed schedule and basic scenario, seven ships are needed to transport the demand from Bremerhaven (DEBRV) to Saint Petersburg (RULED); then two of these seven ships can sail back to Bremerhaven with the demand from Saint Petersburg to Bremerhaven. In total, the network needs seven vessels to serve the leg between these two ports and seven port visits at Saint Petersburg. In the dynamic schedule, the demand from Bremerhaven to Saint Petersburg appears on day 3, while the demand for the opposite direction arrives on day 5. When the network is designed on day 3, the optimization problem acknowledges that there is no demand back from Saint Petersburg to Bremerhaven. Seven vessels are assigned on the leg on day 3 to fulfil the demand requirement. On day 5, two more ships are assigned to sail to Saint Petersburg to bring the demand from Saint Petersburg to Bremerhaven. To sum up, nine vessels are needed in the dynamic sailing schedule to serve the leg that requires only seven vessels under the fixed schedule. The difference in the number of vessels used on the leg explains why the bunker cost and port call cost in the former sailing schedule are considerably higher than those in the latter schedule. This practice happens not only on the Bremerhaven – Saint Petersburg leg but also on other legs whose demands from both sides do not present on the same sailing day.

The time charter cost increases 16% in the basic scenario and 20% in both the low and high scenario when the schedule switches from the fixed, weekly to the flexible schedule. Similar to the bunker cost and port call cost, the rise in the time charter cost is due to the significant increase in the number of vessels in the fleet. In the flexible schedule, the time charter cost is calculated based on the time the vessels are in use, including time sailing at sea and time waiting at port. When a vessel in the dynamic sailing schedule finishes the course of routes to which it is assigned, time charter cost is no longer accumulated on the vessel. On the contrary, the vessels in the fixed schedule are bound to their frequency of the port call at the hub port. When a vessel has a weekly port call frequency at the hub, the time charter cost is counted on the whole week. Similarly, the timer for the charter costs is two weeks for those with the biweekly frequency. This seems to be the reason why the time charter cost pushes up maximum only 20% while the number of vessels in use for the dynamic schedule is nearly double that for the fixed schedule. This logic also explains the increase by a maximum of 26% in the bunker costs in all the three scenarios.

The average capacity utilization rate of the dynamic sailing schedule is comparatively low, that is 52%, 54% and 56% for the low, basic and high scenario, respectively, while the rates in the fixed schedule are above 68%. It is understandable as for the same amount of demand in the network the fixed schedule needs ten vessels in the low and basic scenario and 12 vessels in the high scenario to satisfy the demand requirement, these number in the dynamic schedule are 17, 18 and 21 vessels, respectively. This low fill-up rate reflects the potential disadvantage of the dynamic sailing schedule due to the lack of consolidation possibility, i.e. small demands are transported separately. Moreover, the network asymmetry can be worse when looking at each sailing day as a network on its own. For example, on sailing day 3 in the basic scenario, the ratio of the demand from the hub to the spoke ports to the demand from the spoke ports back to the hub is 2.18. This ratio in the whole Baltic instance is 1.49. The imbalance of the demand on the head-haul and the back-haul leg results in vessels sailings in ballast to relocate for the next shipment.

It seems that the introduction of flexible schedule hurts liner shipping companies from the cost and capacity utilization perspective. The potential advantage of this type of schedule lies in the short lead time that can bring up the service level and customer satisfaction. Figures 13 - 15 show the distribution of lead time, time that demands wait at their departure port, and time demands spend at sea for the two schedules and under the three scenarios.

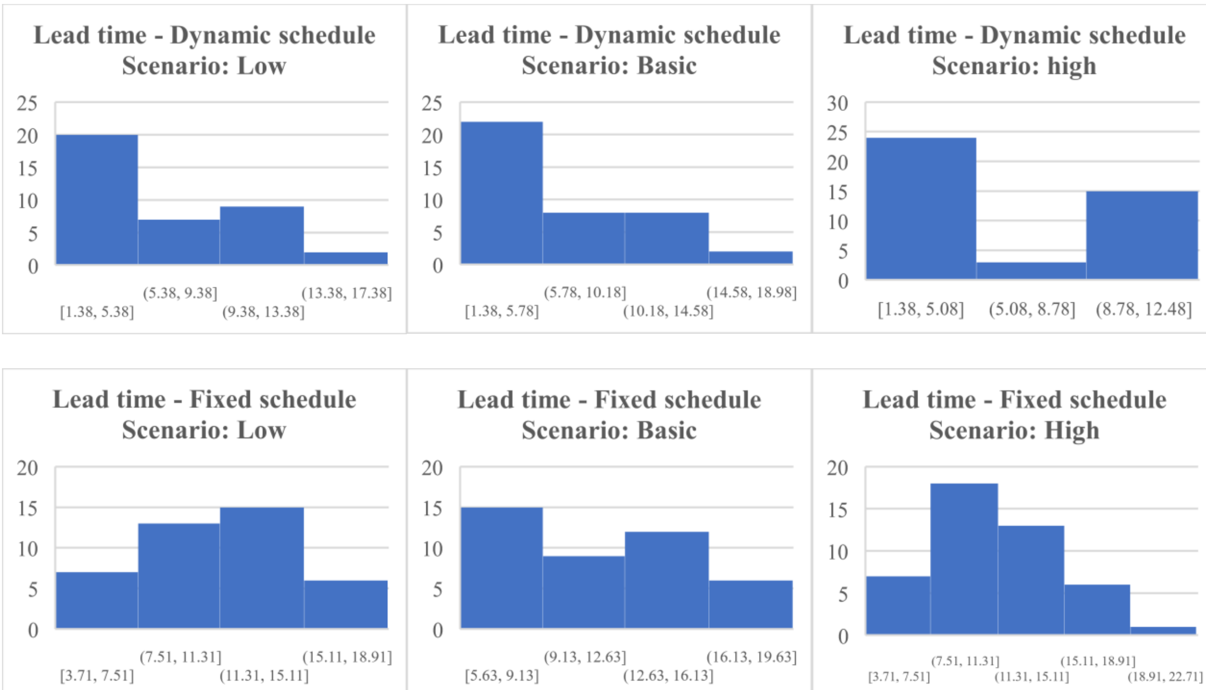

Figure 13. Distribution of lead time for two schedules and three scenarios, in days

The lead time includes both the time that demands wait at their original port and the time they travel at sea. The waiting time at port is counted from the day a demand arrives at its origin to the day it is loaded on a vessel for transportation. The time at sea, or transit time, is the time when a demand stays on a vessel to travel to its origin. In general, the lead time and time that the demands wait at their original port under the dynamic schedule are shorter while the time at sea under both schedules is more or less the same.

The distribution of lead time in the dynamic schedule skews to the left with a long tail to the right, which indicates that most of the demands are transported to their destination port within a short time. In all the scenarios, more than half of the demands reach their target port within 5.78 days. Only a few shipments use more than 13 days to travel to their destination. In the high scenario, no demands spend more than 12.48 days getting to the unloading port after they arrive at their departure port.

In the fixed schedule, the distribution tends to have a bell shape, rather than skewing toward one side. In the low scenario and the high scenario, most of the demands spend from 7.51 to 15.11 days for waiting and being transported. In the high scenario, some containers spend more than 18.91 days travelling to their destination after they are delivered at their origin port. In the basic scenario, no demands use less than 5.63 days for transportation, and quite a few demands spend more than 16.13 days to reach their destination port, counting from the day they arrive at the loading port.

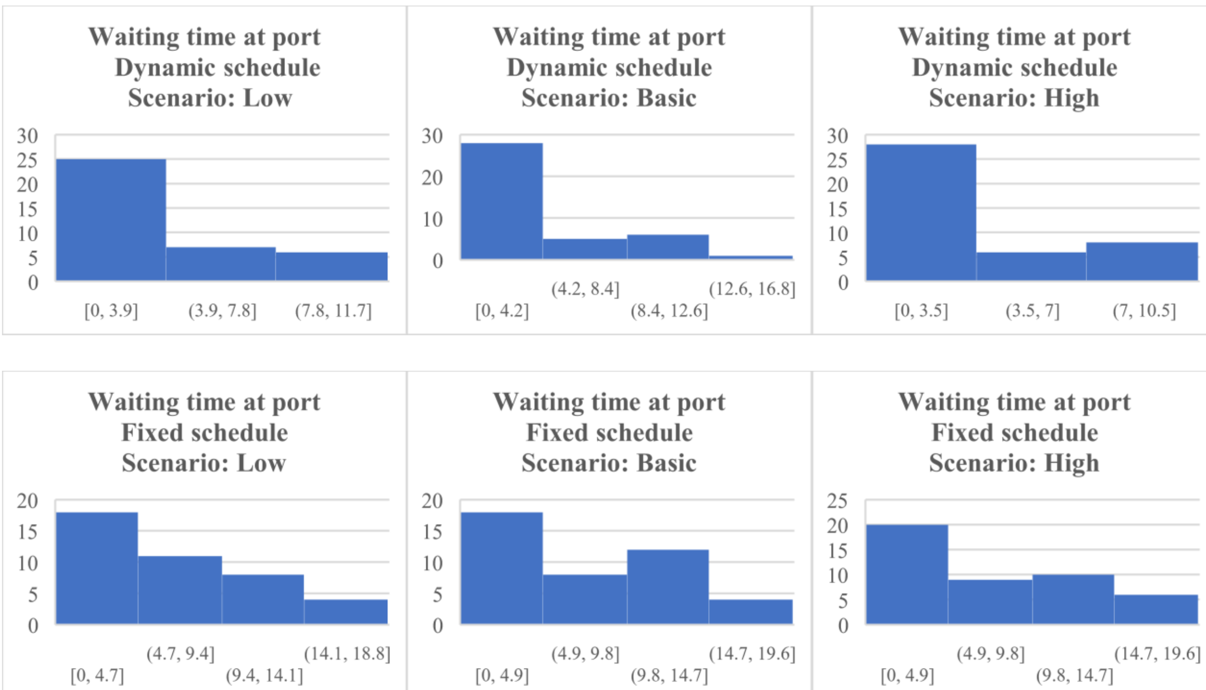

Figure 14. Distribution of waiting time at port for two schedules and three scenarios, in days

In both schedules, the distribution of waiting time at the original port skews to the left, which reflects the practice that liner shipping companies try to ship the demands as soon as possible to reduce the lead time and increase the service level. However, the skewness in the dynamic schedule is far more extreme than that in the fixed schedule. The reason for this is that, in the former schedule, the sailing event is triggered three times during the week, immediately when the threshold is reached. None of the demands from the hub to spokes has to wait more than two days to be loaded on board for the journey to their destination port. The demands that wait longer are those from the spokes back to the hub since they have to wait for the ships to arrive to pick them up. There is a surprise that in the basic scenario, which is the presence of a shipment that waits for over 12.6 days before it is loaded on a vessel. In the low scenario and the high scenario, only a few shipments spend more than 7.8 days at their departure port. Under the fixed schedule, more than half of the demands waits at their original port for over 4.9 days. A few shipments have to spend more than 14.1 days at the departure port before there is an available spot for them on a vessel sailing towards their destination port.

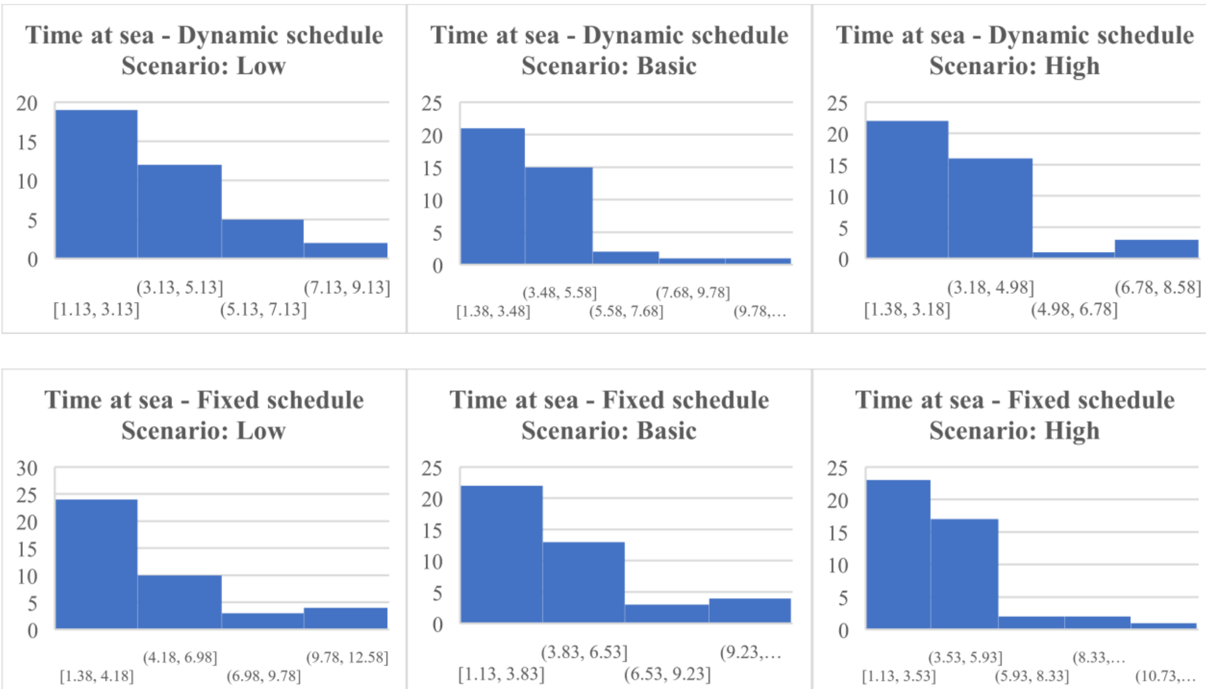

Figure 15. Distribution of demands time at sea for two schedules and three scenarios, in days

Time at sea is the time when the major part of the total cost incurred and where the liner shipping companies have more flexibility to minimize the costs. The cost incurred when a vessel is at a port is somewhat fixed since the time staying at a port is predetermined and identical for all the ports. The mechanism of the optimization of LSNDP tries to minimize the time that a demand spends at sea in an attempt to reduce the total cost. In both schedules, the majority of demands is brought to their destination in a short time after being loaded on board. In the dynamic schedule, it takes less than 5.58 days for most of the demands to arrive at their unloading point in all the three scenarios. Under the fixed schedule, a bit longer time is needed; however, very few shipments use more than 6.98 days to travel to their destination.

6.2.4 Result from the small instance

The absolute optimality resulted from the new instance proves that the result of the model with the original Baltic dataset is reliable, despite the gaps. Since the small instance is not the focus of this thesis, only the basic scenario is run, and the discussion in this part involves only the financial result and the operational effect on lead time.

Regarding the profitability, the fleet of autonomous vessels outperforms that of conventional vessels with the main contribution from the time charter cost and the bunker cost. Among the autonomous fleets, the combination of 200 and 800 FFE vessels also has the best performance, similar to the result from the original instance. The fleet of vessels of 200 FFE capacity shows the lowest profitability, compared to the other fleet configurations with the fixed sailing schedule. However, unlike the result from the Baltic instance with a profit for all the fleet configurations, in the small dataset, only the fleet of autonomous vessels of 450 and 800 FFE and the fleet of 200 and 800 FFE are profitable, and other fleets result in a loss. As mentioned in subchapter 6.2.2, the fleet configuration, which has an impact on the financial performance of liners, should be chosen carefully. When the dynamic schedule is applied, the new policy results in a worse financial result with a huge loss on liner companies.

From the operational perspective, the findings are comparable to those from the run with the original Baltic instance. The lead time under the dynamic schedule is much shorter than that under the fixed schedule due to a significant improvement in the time at the original ports. There is no wide gap between the two schedules in terms of transit time, which is similar to the finding from the original Baltic sea instance. Appendix I shows the detailed result of the small instance.

7 Discussion

7.1 Key findings

The computational experiment shows that switching from conventional vessels may be beneficial for liner shipping companies and lead to cost savings due to higher fuel efficiency of autonomous vessels and lower operating expenses related to crew on board and storages.

The cost-element analysis indicates that the fleet of vessels of 200 FFE and 800 FFE has the best performance among the fleet configurations with the highest profit in all the three scenarios. It seems that the combination of large ships which are used to serve the long legs with high demand volume and small feeders which fit well with short routes and low demand has brought great flexibility to adapt the asymmetric demand of the network. When the demand fluctuates, the fleet's capacity can be adjusted easily by adding up more small feeders or cease the usage of them. This advantage is reflected in the three scenarios in the way that whenever the demand increases, one more vessel of a capacity of 200 FFE is chartered in to take care of the additional demand.

None of the fleet configurations has outperformed the others significantly in terms of capacity utilization. One of the fundamental issues of overseas transportation, not only in the liner shipping business but also in other segments, is the unbalanced demand between the head-haul and the back-haul leg. In the Baltic sea network, the demand from the hub – Bremerhaven (DEBRV) to the other spoke ports is 2,937 FFE, while the demand flowing back is 1,967 FFE. Therefore, when the vessels sail back from the spokes, it is impossible to fill up the existing capacity. Most ships in the class of 450 FFE and 800 FFE have the length of sailing routes of two weeks, which allows them to gather the demand from the multiple spoke ports to increase the fill-up rate on the way back to Bremerhaven (DEBRV). The result from LSNDP over the four fleet configurations also shows the economies of scale effect where the fleet, which includes all small feeders, performs worst, and the total cost decreases when larger vessels are added to the fleet. Despite that, the fleet with vessels of 450 and 800 FFE does not deliver excellent performance, compared to other fleets; instead, it is the second-worst in terms of cost minimization. Indeed, if the capacity of the fleet exceeds the demand in the network substantially, the mismatch will gradually cancel out the benefit of economies of scale. Sailing large vessels in a network where multiple small shipments are involved can hurt the liners since the costs associated with the large capacity is comparatively high. The fleet configuration plays an important role in both economic performance and capacity utilization. While large ships contribute to economies of scales, small vessels provide the flexibility to adjust to the market demand.

Regarding the experiment of a group of small, autonomous feeder sailing in convoy under a dynamic schedule, the result from the dynamic model shows a conflict between the economic loss and the operational benefit. On the one hand, the dynamic schedule outperforms the fixed schedule in terms of transporting time due to a significantly short waiting time that the demands spend at their departure port. On average, the lead time when sailing under a flexible schedule, which counts from the day the demands arrive at their departure port to the day they reach their destination, is only half of that when vessels have a fixed port call schedule. This benefit may help the liner shipping companies which implement the flexible sailing schedule to increase their service level and customer satisfaction. On the other hand, when it comes about minimizing operating cost and increasing the fill-up rate, the dynamic schedule leads to a loss in profit and low capacity utilization of the fleet. An enormous number of vessels are required in order to meet the demand constraint, which causes a substantial rise in all vessel-related costs, including bunker cost, variable port call cost and time charter cost. The problem of overcapacity is severe due to the lack of consolidation possibility for small demands. Moreover, many vessels sail between ports in ballast to relocate their position for the next shipment as the network asymmetry on one sailing day can be much worse than the imbalance of the whole Baltic sea instance. It should be acknowledged that the result from the flexible sailing schedule is affected by the choice of the threshold level. The trigger's value of 75% of the basic fleet's capacity that is 1,500 FFE is reasonable since it allows a sufficient volume of demand to be gathered in the network so that it is worth starting the sailing. At the same time, it does not hold up the sailing process too long to dismiss the benefit of the dynamic sailing schedule, i.e. short waiting time at departure ports.

7.2 Limitations

As autonomous maritime transportation industry is still on an early stage of development, limitations due to the conceptual nature of unmanned vessels exist. The uncertainties are mainly related to the cost parameters of autonomous ships that are based on estimates and assumptions derived from existing literature. Some cost components of autonomous ships, such as shore control center and maintenance crew costs, are difficult to estimate and, therefore, are ignored.

In both the model for a fixed sailing schedule and the model for a flexible sailing schedule, transshipment is not allowed. The reason for this is to simplify the problem due to the timing issue at the butterfly port. However, transshipment practice is an important feature of the liner shipping business; removing transshipment in the model restricts the possibility to construct complex routes, which give a chance to lower costs. Besides the transshipment matter, the two models also do not take into account the container costs, particularly costs regarding the repositioning of empty containers. The omission of container costs in the thesis is due to the complexity of the problem. Including costs related to containers and the repositioning of unused containers will enormously complicate the intractable LSNDP. Additionally, empty container repositioning problem itself is a challenging topic which has attracted researchers' attention and will not be solved to the desired result in a short time. Therefore, although the lack of container-related costs in the model is a limitation, it can be wise to focus on the LSNDP first and leave the question of container reposition for the future research.

Implementing a dynamic model to solve the LSNDP has not been explored by researchers before. Despite the attempt to replicate the liner shipping business in the dynamic model, it is difficult to maintain both the feasibility and the complexity of the problem. The model has been simplified such that a sufficiently good result can be reached, which, of course, brings along some limitations. One of the drawbacks of the dynamic model is that it does not allow the network to adapt to new information after the services for the existing demands have been decided; in other words, the model is not based on real-time demand. This disadvantage leads to a necessity of extra capacity to meet the demand requirement, which pushes up the total cost of the network and brings down the utilization of vessels. The choice of threshold level also has an effect on the performance of the network in the dynamic sailing schedule since it affects the demand volume when the sailing action takes place, i.e. the existing demand volume must be equal to or higher than the trigger. On the one hand, if the threshold is too low, the vessels will sail more frequently, which shortens the lead time and increases the service level. However, only a few demands appear when the threshold is reached; this means lesser possibilities to consolidate small shipments to fill up the vessels' space and reduce costs. On the other hands, if the threshold is too high, the flexible schedule gets close to the fixed sailing schedule, and all the benefits of the short lead time disappear. The choice of the threshold value in this thesis is based on the experience from the fixed schedule in an attempt to reach the balance between the possibility for both consolidating small demands and cutting down the waiting time at port. However, an elaborate experiment to pick the optimal value of the threshold has not been conducted.

7.3 Future research

Liner shipping companies are currently operating with a weekly or biweekly sailing schedule, which gives them better control over designing the sailing services but also a low service level due to a long lead time. A flexible sailing schedule can be a solution to improve customer satisfaction; however, the gain in service level must go in hand with the financial result. The model in this thesis is the first attempt to address the LSNDP with a dynamic model, which still has limitations that can be overcome to achieve a more desirable result. One of the factors that affect the result of the flexible sailing schedule is the value of the trigger that allows the sailing action. As mentioned above, the trigger value is picked carefully, but an experiment may be conducted to investigate the designed network's performance under different trigger values.

Another limitation lies in the simplification, which is necessary to ensure the feasibility of the model. However, a more complicated model should be tested in order to reflect better the liner shipping business. A suggestion that should be considered is to incorporate the transshipment practice into the dynamic model. The transshipment activity can provide liner shipping companies with an opportunity to bring down the total cost, which is vital to make the flexible sailing schedule feasible. The transshipment service is also likely to offer the opportunity to shorten the lead time, which will enhance the benefit of the flexible sailing schedule on customer satisfaction.

Another point that should be addressed in future research related to the dynamic model is the ability to adapt to real-time demand. The dynamic model in this thesis is built on the principle that a dynamic model is a sequence of static models. The model itself does not evolve along with new information, particularly new demand arrival. It will be interesting to see if a dynamic model that can respond to real-time demand can perform better in terms of both economics measures and service level.

The problem of empty container repositioning has also drawn attention from researchers in the operation research field. The introduction of autonomous ships into this problem may bring in new perspectives. In particular, benefits from a fleet of autonomous ships specialized in repositioning empty containers among the ports in a market and having its operation separated from the demand flow may be studied. In addition, the fleet may not sail under a fixed schedule but only when the container stock is down to a certain level, which triggers the need for restocking empty, ready-to-use containers.

8 Conclusion

This thesis aims to investigate the effects of introducing autonomous vessels in the LSNDP, from both economic and operational perspective. Two models are built to run multiple experiments on the Baltic instance, which is introduced by Brouer et al. (2014a), with different fleet combinations of three capacity level, including 800 FFE, 450 FFE and 200 FFE. The static model provides a basis for comparison of the economic performance between the conventional fleet and autonomous fleet, and among various fleet configurations. While the economic benefit of switching from regular to unmanned vessels in a fixed sailing schedule has been discussed in a few studies, the introduction of a flexible sailing schedule designed by a dynamic model is rather fresh. The two sailing schedules are compared in terms of profit and service level, which is measured by the lead time.

The results from the experiments show that, with a fixed sailing schedule, a fleet of autonomous vessels incurs a lower operating cost than a fleet of regular, crewed ships due to the cost savings from bunker cost and time charter cost. Among the fleet configurations, the fleet of 800 and 200 FFE vessels outperforms the other fleet in terms of profitability. The fleet of only 200 FFE ships has the lowest profit due to the substantial number of vessels needed to meet the demand for transportation. The considerable difference in the profit between the best and the worst performing fleets suggests that the fleet structure should be chosen carefully. A wrong choice of fleet configuration can push up the operating cost of the network significantly. The result from a dynamic sailing schedule carried out by the fleet of vessels of 200 FFE is compared with that from the fixed schedule to test the idea of small autonomous ships sailing in convoy based on the demand level in the network. The experiments propose that while the flexible schedule offers an advantage in terms of service level with considerably shorter lead time than the fixed schedule, this benefit imposes a massive extra cost on liner shipping companies.

Although all the experiments have been carefully conducted, there are still some limitations in the data and models. The uncertainties connected to autonomous vessels costs, the lack of transshipment in both the dynamic and the fixed sailing schedule, the inflexibility of the dynamic model and the problem of container repositioning may restrict the implication of the results in this thesis. However, these limitations also give an opening start for further research in the field of autonomous shipping. This thesis is, to the knowledge of the authors, the first attempt to address the potential of combining autonomous ships with a dynamic sailing schedule. Further research needs to be carried out in order to explore this potential and turn it into reality.

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Appendices

Appendix A. Sheridan levels of autonomy (Rolls-Royce, 2016)

Level	Description
10	The computer does everything autonomously, ignores human
9	The computer informs human only if it (the computer) decides so
8	The computer informs human only if asked
7	The computer executes automatically, when necessary informing human
6	The computer allows human a restricted time to veto before automatic execution
5	The computer executes the suggested action if human approves
4	Computer suggests single alternative
3	Computer narrows alternatives down to a few
2	The computer offers a complete set of decision alternatives
1	The computer offers no assistance, human in charge of all decisions and actions

Appendix B. Autonomy levels according to the Lloyd's Register (2017)

Level	Description
AL 0	Manual: No autonomous function. All action and decision-making performed manually (n.b. systems may have level of autonomy, with Human in/ on the loop.), i.e. human controls all actions.
AL 1	On-board Decision Support: All actions taken by human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data is provided by systems on board.
AL 2	On &Off-board Decision Support: All actions taken by human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off-board.
AL 3	'Active' Human in the loop: Decisions and actions are performed with human supervision. Data may be provided by systems on or off-board.
AL 4	Human on the loop, Operator/ Supervisory: Decisions and actions are performed autonomously with human supervision. High impact decisions are implemented in a way to give human Operators the opportunity to intercede and over-ride.
AL 5	Fully autonomous: Rarely supervised operation where decisions are entirely made and actioned by the system.
AL 6	Fully autonomous: Unsupervised operation where decisions are entirely made and actioned by the system during the mission.

Appendix C. Demands between ports, FFE per week

Origin	Destination	FFE Per Week
DEBRV	DKAAR	456
DEBRV	NOSVG	65
DEBRV	NOAES	10
DEBRV	PLGDY	98
DEBRV	NOBGO	17
DEBRV	RUKGD	268
DEBRV	FIRAU	18
DEBRV	FIKTK	187
DEBRV	SEGOT	597
DEBRV	RULED	1,215
DEBRV	NOKRS	6
DKAAR	DEBRV	397
FIKTK	DEBRV	162
FIRAU	DEBRV	77
NOAES	DEBRV	50
NOBGO	DEBRV	37
NOKRS	DEBRV	16
NOSVG	DEBRV	32
PLGDY	DEBRV	231
RUKGD	DEBRV	7
RULED	DEBRV	298
SEGOT	DEBRV	660

Appendix D.

Table D1. Sailing time of conventional vessels with capacity of 450 FFE, hours

Ports	DEBRV	DKAAR	FIKTK	FIRAU	NOAES	NOBGO	NOKRS	NOSVG	PLGDY	RUKGD	RULED	SEGOT
DEBRV	.	37	90	88	45	37	24	31	64	69	98	30
DKAAR	37	.	66	65	48	36	18	29	34	38	68	12
FIKTK	90	66	.	45	98	88	71	81	43	40	9	60
FIRAU	88	65	45	.	99	87	69	80	51	57	51	65
NOAES	45	48	98	99	.	14	33	23	74	80	108	38
NOBGO	37	36	88	87	14	.	19	9	62	68	97	29
NOKRS	24	18	71	69	33	19	.	12	45	50	79	11
NOSVG	31	29	81	80	23	9	12	.	55	61	90	22
PLGDY	64	34	43	51	74	62	45	55	.	6	48	39
RUKGD	69	38	40	57	80	68	50	61	6	.	48	44
RULED	98	68	9	51	108	97	79	90	48	48	.	70
SEGOT	30	12	60	65	38	29	11	22	39	44	70	.

Table D2. Sailing time of conventional vessels with capacity of 800 FFE, hours

Ports	DEBRV	DKAAR	FIKTK	FIRAU	NOAES	NOBGO	NOKRS	NOSVG	PLGDY	RUKGD	RULED	SEGOT
DEBRV	.	32	77	76	39	32	21	26	54	59	84	26
DKAAR	32	.	57	55	41	31	16	25	29	33	59	10
FIKTK	77	57	.	39	84	76	61	70	37	34	8	52
FIRAU	76	55	39	.	85	75	59	69	43	48	44	56
NOAES	39	41	84	85	.	12	28	20	64	69	92	32
NOBGO	32	31	76	75	12	.	16	8	53	58	83	25
NOKRS	21	16	61	59	28	16	.	10	38	43	68	10
NOSVG	26	25	70	69	20	8	10	.	47	52	77	19
PLGDY	54	29	37	43	64	53	38	47	.	5	41	33
RUKGD	59	33	34	48	69	58	43	52	5	.	41	38
RULED	84	59	8	44	92	83	68	77	41	41	.	60
SEGOT	26	10	52	56	32	25	10	19	33	38	60	

Appendix E. Operating costs associated with ports, USD

Port	Lifting cost per FFE	Port call cost per FFE	Fixed port call cost, conventional vessels	Fixed port call cost, autonomous vessels
DEBRV	199	14	1,1795	14,154
DKAAR	429	7	11,861	14,233
FIKTK	137	52	1,182	1,418
FIRAU	196	127	18,552	22,262
NOAES	684	130	24,098	28,918
NOBGO	365	119	17,435	20,922
NOKRS	141	180	24,076	28,891
NOSVG	315	13	1,227	1,472
PLGDY	84	138	23,817	28,580
RUKGD	233	27	1,062	1,274
RULED	270	37	722	866
SEGOT	247	13	26,838	32,206

Appendix F. Operating costs associated with ports, USD

Vessel class	Capacity, FFE	Design speed, knots	Bunker ton per day at design speed, tons	TC rate daily, USD
Feeder, 450 FFE	450	12	18.8	5,000
Feeder, 800 FFE	800	14	23.7	8,000
Panamax, 1200 FFE	1,200	18	52.5	11,000
Panamax, 2400 FFE	2,400	16	57.4	21,000
Post Panamax	4,200	16.5	82.2	35,000
Super Panamax	7,500	17	126.9	55,000

Appendix G. Service structure with the fixed sailing schedule

Table G1. Service structures generated by the LSNDP in the low scenario

Fleet	Vessel number	Capacity, FFE	Service type	Route
Regular (450 and 800 FFE)	1	450	Simple	DEBRV – FIRAU – PLGDY – NOKRS – NOBGO – NOAES – DEBRV
	2	800	Butterfly	DEBRV – RUKGD – FIKTK – RULED – DEBRV – SEGOT – DEBRV
	3	800	Butterfly	DEBRV – DKAAR – DEBRV – RULED – NOSVG – DEBRV
Autonomous (450 and 800 FFE)	1	450	Simple	DEBRV – FIRAU – PLGDY – NOKRS – NOBGO – NOAES – DEBRV
	2	800	Butterfly	DEBRV – RUKGD – RULED – DEBRV – DKAAR – DEBRV
	3	800	Butterfly	DEBRV – FIKTK – RULED – DEBRV – SEGOT – NOSVG – DEBRV
Autonomous (200 and 450 FFE)	1	200	Simple	DEBRV – FIRAU – NOKRS – NOSVG – NOBGO – NOAES – DEBRV
	2	450	Butterfly	DEBRV – RULED – FIKTK – DEBRV – SEGOT – DEBRV
	3	450	Butterfly	DEBRV – DKAAR – DEBRV – RULED – DEBRV
	4	450	Butterfly	DEBRV – RULED – PLGDY – DEBRV – SEGOT - DEBRV
	5	450	Simple	DEBRV – RUKGD - DEBRV
Autonomous (200 and 800 FFE)	1	200	Simple	DEBRV – FIRAU – NOKRS – NOSVG – NOBGO – NOAES – DEBRV
	2	800	Butterfly	DEBRV – DKAAR – DEBRV – RULED – PLGDY – DEBRV
	3	800	Butterfly	DEBRV – RULED – FIKTK – RUKGD – DEBRV – SEGOT – DEBRV
Autonomous (200 FFE)	1	200	Simple	DEBRV – PLGDY – DEBRV
	2	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	3	200	Butterfly	DEBRV – NOSVG – SEGOT – DEBRV – RUKGD – DEBRV
	4	200	Simple	DEBRV – RUKGD – RULED – NOSVG – DEBRV
	5	200	Simple	DEBRV – RULED – PLGDY – NOBGO – DEBRV
	6	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	7	200	Simple	DEBRV – DKAAR – NOKRS – NOSVG – DEBRV
	8	200	Butterfly	DEBRV – DKAAR – DEBRV – FIKTK – DEBRV
	9	200	Simple	DEBRV – RULED – FIRAU – DKAAR – DEBRV
	10	200	Simple	DEBRV – RULED – NOAES – DEBRV

Table G2. Service structures generated by the LSNDP in the basic scenario

Fleet	Vessel number	Capacity, FFE	Service type	Route
Regular (450 and 800 FFE)	1	450	Simple	DEBRV – NOAES – RUKGD – PLGDY – NOKRS – NOBGO – DEBRV
	2	800	Butterfly	DEBRV – RULED – FIKTK – DEBRV – SEGOT – NOSVG – DEBRV
	3	800	Butterfly	DEBRV – DKAAR – DEBRV – FIRAU – RULED – DEBRV
Autonomous (450 and 800 FFE)	1	450	Simple	DEBRV – NOBGO – NOKRS – RUKGD – PLGDY – NOAES – DEBRV
	2	800	Butterfly	DEBRV – RULED – FIKTK – DEBRV – SEGOT – NOSVG – DEBRV
	3	800	Butterfly	DEBRV – DKAAR – DEBRV – FIRAU – RULED – DEBRV
Autonomous (200 and 450 FFE)	1	200	Simple	DEBRV – RULED – FIRAU – NOKRS – DEBRV
	2	200	Butterfly	DEBRV –NOAES – NOBGO – NOSVG – DEBRV
	3	450	Butterfly	DEBRV –DKAAR – DEBRV – RULED – FIKTK – DEBRV
	4	450	Butterfly	DEBRV – RULED – PLGDY – DEBRV – SEGOT – DEBRV
	5	450	Simple	DEBRV – RUKGD – DEBRV
	6	450	Butterfly	DEBRV –DKAAR – RULED – DEBRV – SEGOT - DEBRV
Autonomous (200 and 800 FFE)	1	200	Simple	DEBRV – NOSVG – NOBGO – NOAES - DEBRV
	2	200	Simple	DEBRV – RULED – FIRAU – NOKRS – DEBRV
	3	800	Butterfly	DEBRV – RULED – FIKTK – RUKGD – DEBRV – SEGOT – DEBRV
	4	800	Butterfly	DEBRV – DKAAR – DEBRV – RULED – PLGDY – DEBRV
Autonomous (200 FFE)	1	200	Simple	DEBRV – RULED – FIRAU – NOKRS – DEBRV
	2	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	3	200	Simple	DEBRV – RULED – NOAES – DEBRV
	4	200	Simple	DEBRV – RULED – PLGDY – RUKGD – SEGOT – DEBRV
	5	200	Butterfly	DEBRV – DKAAR – DEBRV – FIKTK – DEBRV
	6	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	7	200	Butterfly	DEBRV – RUKGD – PLGDY – DEBRV – SEGOT – DKAAR – DEBRV
	8	200	Butterfly	DEBRV – DKAAR – DEBRV – RUKGD – NOSVG – DEBRV
	9	200	Simple	DEBRV – NOBGO – NOSVG – RULED – DEBRV
	10	200	Simple	DEBRV – NOSVG – RUKGD – RULED – DEBRV

Table G3. Service structures generated by the LSNDP in the high scenario

Fleet	Vessel number	Capacity, FFE	Service type	Route
Regular (450 and 800 FFE)	1	450	Simple	DEBRV – RULED – NOSVG – NOAES – DEBRV
	2	450	Simple	DEBRV – FIKTK – RULED – FIRAU – NOKRS – DEBRV
	3	450	Butterfly	DEBRV – DKAAR – DEBRV – RUKGD – PLGDY – NOBGO – DEBRV
	4	800	Butterfly	DEBRV – DKAAR – SEGOT – NOSVG – DEBRV – RULED – DEBRV
Autonomous (450 and 800 FFE)	1	450	Simple	DEBRV – FIKTK – FIRAU – NOBGO – DEBRV
	2	450	Simple	DEBRV – RUKGD – PLGDY – NOKRS – NOAES – DKAAR – DEBRV
	3	800	Butterfly	DEBRV – RULED – NOSVG – DEBRV – SEGOT – NOSVG – DEBRV
	4	800	Butterfly	DEBRV – DKAAR – DEBRV – NOSVG – RULED – DEBRV
Autonomous (200 and 450 FFE)	1	200	Simple	DEBRV – FIRAU – RULED – NOKRS – DEBRV
	2	200	Simple	DEBRV – FIKTK – NOBGO – NOAES – DEBRV
	3	450	Butterfly	DEBRV – NOSVG – DKAAR – DEBRV – RUKGD – PLGDY – DEBRV
	4	450	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	5	450	Butterfly	DEBRV – DKAAR – DEBRV – RULED – FIKTK – DEBRV
	6	450	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
Autonomous (200 and 800 FFE)	1	200	Simple	DEBRV – RUKGD – PLGDY – NOBGO – NOSVG – NOAES – DEBRV
	2	200	Simple	DEBRV – FIRAU – RULED – RUKGD – DEBRV
	3	200	Simple	DEBRV – RUKGD – NOKRS – NOSVG – PLGDY – DEBRV
	4	800	Butterfly	DEBRV – FIKTK – RULED – DEBRV – SEGOT – NOSVG – DEBRV
	5	800	Butterfly	DEBRV – DKAAR – DEBRV – RULED – NOSVG - DEBRV
Autonomous (200 FFE)	1	200	Butterfly	DEBRV – DKAAR – DEBRV – FIKTK – DEBRV
	2	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	3	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	4	200	Simple	DEBRV – DKAAR – NOBGO – DEBRV
	5	200	Simple	DEBRV – RUKGD – RULED – NOSVG – DEBRV
	6	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	7	200	Butterfly	DEBRV – NOSVG – DKAAR – DEBRV – RUKGD – DEBRV
	8	200	Simple	DEBRV – FIKTK – RULED – PLGDY – NOSVG – DEBRV
	9	200	Butterfly	DEBRV – RULED – DEBRV – SEGOT – DEBRV
	10	200	Simple	DEBRV – RULED – NOAES – DEBRV
	11	200	Simple	DEBRV – PLGDY – DEBRV
	12	200	Simple	DEBRV – RULED – FIRAU – NOKRS - DEBRV

Appendix H. Service structure with the dynamic sailing schedule

Scenario	Sailing day	# sailing vessel	Service type	Route
Low	3	3	Simple	DEBRV – RULED – DEBRV
		1	Simple	DEBRV – RULED – FIRAU – DEBRV
		1	Simple	DEBRV – RULED – FIKTK – SEGOT – DEBRV
		1	Simple	DEBRV – RUKGD – DEBRV
		1	Simple	DEBRV – RULED – SEGOT – DEBRV
		1	Simple	DEBRV – NOSVG – NOBGO – NOAES – DEBRV
		1	Simple	DEBRV – PLGDY – RUKGD – FIKTK – SEGOT – DEBRV
	5	2	Simple	DEBRV – DKAAR – DEBRV
		1	Simple	DEBRV – SEGOT – RULED – NOKRS – DEBRV
		1	Simple	DEBRV – SEGOT – RULED – DKAAR – DEBRV
		1	Simple	DEBRV – NOSVG – DEBRV
		1	Simple	DEBRV – SEGOT – DEBRV
	7	1	Simple	DEBRV – NOAES – NOBGO – PLGDY – DEBRV
		1	Simple	DEBRV – FIRAU – FIKTK – RUKGD – PLGDY – DEBRV
Basic	3	2	Simple	DEBRV – RULED – DEBRV
		1	Simple	DEBRV – RULED – FIRAU – DEBRV
		3	Simple	DEBRV – RULED – SEGOT – DEBRV
		1	Simple	DEBRV – FIKTK – SEGOT – DEBRV
		1	Simple	DEBRV – PLGDY – RUKGD – DEBRV
		1	Simple	DEBRV – RUKGD – RULED – NOSVG – NOBGO – NOAES – DEBRV
	5	2	Simple	DEBRV – SEGOT – DEBRV
		1	Simple	DEBRV – SEGOT – RULED – DEBRV
		1	Simple	DEBRV – DKAAR – DEBRV
		1	Simple	DEBRV – DKAAR – RULED – DEBRV
		1	Simple	DEBRV – NOSVG – NOKRS – DKAAR – DEBRV
	7	1	Simple	DEBRV – PLGDY – DEBRV
		1	Simple	DEBRV – NOBGO – NOAES – DEBRV
		1	Simple	DEBRV – FIRAU – FIKTK – RUKGD – PLGDY – DEBRV
High	3	4	Simple	DEBRV – RULED – DEBRV
		1	Simple	DEBRV – FIKTK – SEGOT – DEBRV
		1	Simple	DEBRV – PLGDY – NOSVG – NOBGO – NOAES – DEBRV
		2	Simple	DEBRV – RULED – SEGOT – DEBRV
		1	Simple	DEBRV – RUKGD – FIKTK – SEGOT – DEBRV
		1	Simple	DEBRV – RUKGD – DEBRV
		1	Simple	DEBRV – RULED – FIRAU – DEBRV
	5	1	Simple	DEBRV – SEGOT – RULED – DEBRV
		2	Simple	DEBRV – SEGOT – DEBRV
		1	Simple	DEBRV – DKAAR – RULED – DEBRV

Appendix H (continued). Service structure with the dynamic sailing schedule

Scenario	Sailing day	# sailing vessel	Service type	Route
		1	Simple	DEBRV – NOSVG – NOKRS – SEGOT – DEBRV
		2	Simple	DEBRV – DKAAR – DEBRV
	7	1	Simple	DEBRV – NOAES – NOBGO – RUKGD – PLGDY – DEBRV
		1	Simple	DEBRV – PLGDY – DEBRV
		1	Simple	DEBRV – FIRAU – FIKTK – DEBRV

Appendix I. Result from the small instance

Table I1. Economic performance

Fleet configuration	Profit	Revenue	Total cost	Bunker cost	Port call cost	Time charter	Lifting cost
Regular 450_800, incl.:	-95	2,498	2,593	305	560	224	1,504
Feeders of 450 FFE				-	-	-	-
Feeders of 800 FFE				*305*	*560*	*224*	
Autonomous 450_800, incl.:	4	2,498	2,494	287	587	116	1,504
Feeders of 450 FFE				-	-	-	-
Feeders of 800 FFE				*287*	*587*	*116*	
Autonomous 200_450, incl.:	-24	2,498	2,522	379	515	124	1,504
Feeders of 200 FFE				*25*	*107*	*15*	
Feeders of 450 FFE				*354*	*408*	*109*	
Autonomous 200_800, incl.:	58	2,498	2,440	308	478	150	1,504
Feeders of 200 FFE				*160*	*330*	*92*	
Feeders of 800 FFE				*148*	*148*	*58*	
Autonomous 200	-210	2,498	2,708	383	607	214	1,504
Autonomous 200 - dynamic	-566	2,498	3,064	531	746	283	1,504

Figure I2. Service level