The choice of feeder container ships for the North Sea and Baltic Sea region

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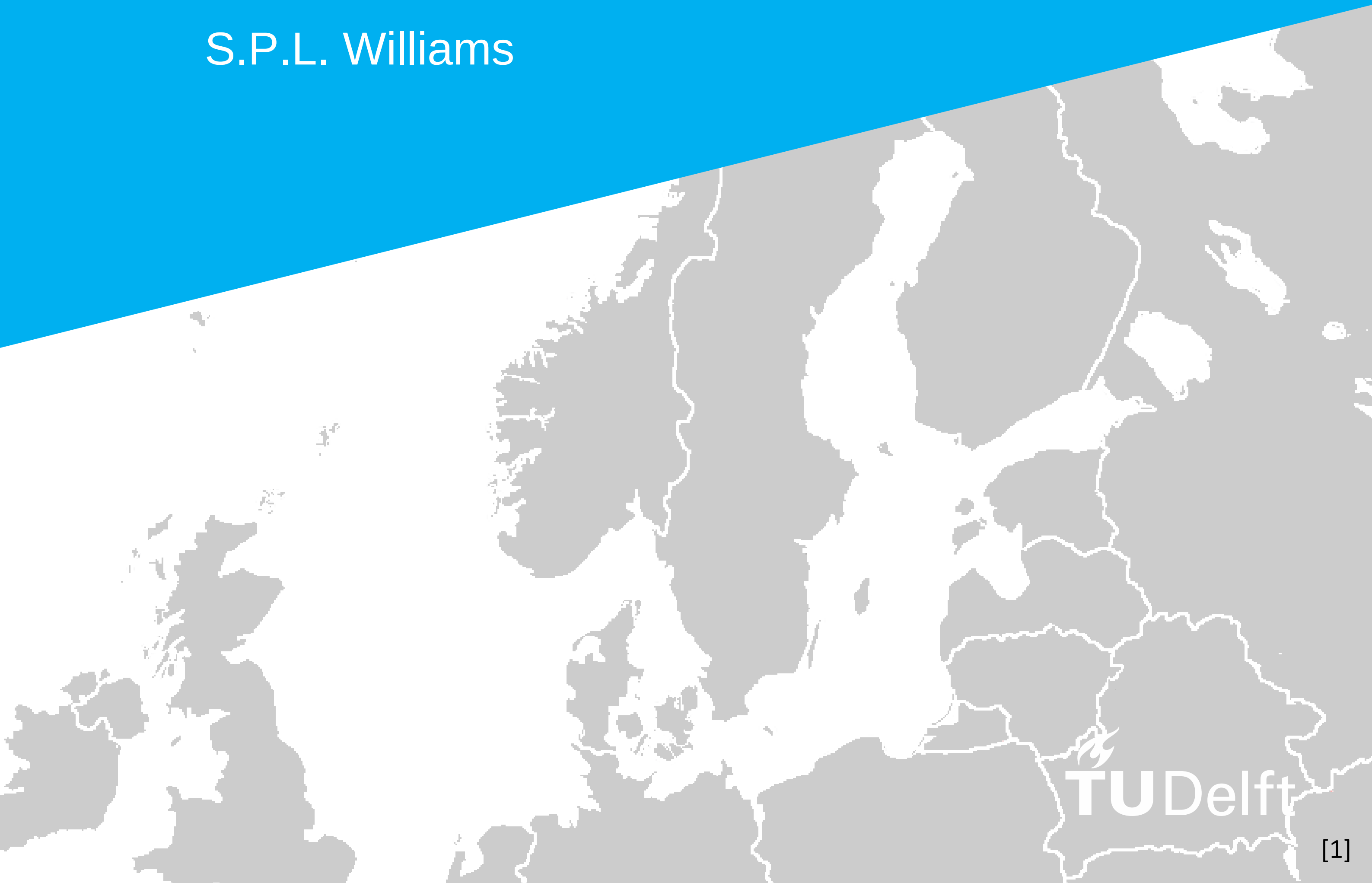

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The choice of feeder container ships for the North Sea and Baltic Sea region

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Abbreviations

AHP Analytical hierarchy process

BC Bunker costs

B Beam

C_b Block coefficient

CaC Canal costs

CC Capital costs

Dwt Deadweight tonnage

GT Gross tonnage

IWT Inland water transport

km/h Kilometer per hour

kn Knot

LSFD Liner shipping fleet deployment

Lwl Length of the water line

MDO Marine diesel oil

MGO Marine gas oil

MIP Mixed integer programming

MLP Multinomial logit programming

NM Nautical mile

OC Operating costs

OD Origin-destination

Pb Brake horsepower

PC Port costs

SFC Specific fuel consumption

TEU Twenty-foot equivalent units

T Draft

ULCS Ultra large container ships

VLCS Very large container ships

VLSFO Very low sulphur fuel oil

Vm Under water volume of the ship

Acknowledgements

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S.P.L. Williams
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Summary

Container ships are becoming larger and larger, but also more numerous. As a result, these large ships are pushing their smaller counterparts down the line, until these smaller ships are no longer efficient for trade routes. The focus area of this thesis is on the North Sea and Baltic Sea area, in particular the area between the West coast of Norway to the Russian part of the Gulf of Finland, with most countries in between with feeder activities between them and North European gateway hubs. This area is seeing an increase in port development. As a result, routes that container ships take are being changed. Either larger ships are coming into the region and stopping at more ports, or they are utilised as feeder ships in the region. This thesis aims to investigate the cascading effect of container ships, regarding the choice of feeder ships between German North Sea ports and feeder destinations in Scandinavian countries and countries on the Baltic Sea. To achieve this, an optimisation model is created that calculates differing total costs for container ships with capacities ranging between 200 and 5000 Twenty-foot Equivalent Units (TEU) in the region. This is done by assigning ships to container flows from German North Sea ports to feeder ports in the region, and allowing the model to choose which arcs are used to fulfill the container inflow of the destination ports. To analyse the impact of each ship type regarding the total cost of their routes taken, ship types are tested separately. Experiments have been run for increasing bunker costs based on existing data, for increasing amounts of container inflows, and decreasing the number of ports based on an increase of minimum container inflow.

The results of the experiments varying bunker costs show the total cost to fulfill all container inflows for each feeder ship type is highly dependant on its utilisation of the Kiel Canal. The Kiel Canal restricts the choice of ships with capacities larger than 1250 TEU. The extra time spent for sailing around the Northern tip of Denmark has a negative effect on the largest ships chosen for this thesis. For an increasing bunker cost, a 1500 TEU capacity ship is hindered more negatively than a 5000 TEU ship due to the Kiel Canal. For variations in volume of container flows, the same impact of the Kiel Canal is also seen. However, total costs start to favour the largest ships chosen, with the largest capacity ship (5000 TEU) having the lowest total costs calculated for a 300% of the original chosen container flows. For decreasing the number of ports from the set based on their container inflow, the largest capacity ships have the lowest total costs from a minimum container inflow of around 400 TEU per week. From this, with current flows and within the near future, it is estimated that the current fleet of around 1000 - 1250 TEU capacity container ships will maintain their position within the North Sea and Baltic Sea region. However, for routes with a substantial container flow volume, larger capacity ships are estimated to be more cost competitive than their smaller counterparts.

This conclusion is based on experiments with only one ship size available for all container flows, with the assumption that all chosen ships are not restricted by berth sizes in ports. Furthermore, all flows originate from German North Sea ports. Recommendations for future researches should take all chosen ship types into consideration for arc-flow pairing, and have more origins for container flows. If all ship types are taken into consideration, size restrictions of ports and transshipment between ship types should also be implemented. Origins included should include other major hubs in the region, as well as from outside the region, as an incoming flow. This would allow for an investigation into large container ships sailing between the current chosen origin hub and large ports, and the consequence on the region as a whole.

1 Introduction

In 2017 the first Ultra Large Container Ships (ULCS) with a capacity exceeding 20,000 twenty-foot equivalent units (TEUs) were delivered. In the three years following, the maximum capacity has increased incrementally. In 2020, Hyundai Merchant Marine put 7 ships into commission with a carrying capacity of 23,964 TEU. In 2023 the 24,000 TEU barrier is planned to be breached, according to the current order book and then the next milestone can be set [33]. An ever growing world economy is driving this increase, with new ships being ordered by companies to be able to compete, as these ships are able to offer an economy of scale, such that smaller ships are no longer able to compete with decreasing freight rates [46]. Where the upper limit will finalise is unknown and has been discussed since the early 1970's. Ge et al. present a list of papers, each following the next, that increases the maximum theoretical capacity of a container ship. Early optimal sizes are based on the particular routes ships operate on and minimisation of transportation costs [42]. Later papers point out that at a certain point the scale of economy diminishes, as to be the maximum size operable. What this maximum capacity is, depends on a variety of factors at that time. Be it either the demand of containers for a certain route, the size restrictions at the end of the chain, or the size restrictions during the trip [47, 70]. It is estimated that by 2025 the average size of container ships on the Far East to Europe, Transatlantic and Latin America to Asia routes are to be 16,000, 10,000 and 12,000 TEU respectively [53]. A report by the International Transport Forum (ITF) goes further to state that around 10% of ships will have a capacity of 14,000 TEU by 2025 [5].

These larger ships are replacing the previous largest ships on main East West trade lines. Ships that were previously the largest were designed for these main trade lines 10 to 15 years ago. The replaced ships are no longer adequately sized to compete with ULCS. By 2015 the smallest ship sailing on the Far East-Europe route was 4,400 TEU [5]. Smaller vessels are increasingly being deployed in other regions and routes where ports are not equipped to handle very large container ships (VLCS) and ULCS. These smaller ships are relegated to other routes that in turn are seeing an increase in container use, notably on the North South trade lines [70]. However, not every port on the North South lines is suited to receive larger capacity ships, either due to size restrictions for the ships, or lack of space for containers on dockside [70]. The same can be said for ULCS on the main East West trade lines as ports are attempting to upgrade their facilities to receive the largest ships. Ports in the Le Havre-Hamburg range are not immune to this trend. However these ports are themselves gateway ports for Northern and Western Europe [5]. Facilities that are no longer suited for feeder ships, may mean that other (larger) ships can be used as feeder ships for the Baltic Sea and North Sea. Due to the cascading effect, small ports in Northern Europe are under threat. Large ships are not capable of berthing there, nor is the container inflow large enough to warrant larger ships than current use [54]. It is therefore important to investigate under which circumstances larger container ships replace their smaller counterparts in Northern Europe.

The goal of this thesis is to investigate the cascading effect of container ships on the choice of feeder ships between European gateway ports and feeder ports in Scandinavian countries and countries on the Baltic Sea. An optimisation model is used to solve a liner shipping network design problem so to determine the choice of ship by minimising total costs per ship, whilst fulfilling container flows between the origin and destination ports. Ship types are tested, independent of each other, to gauge their corresponding impact for the varying parameters.

To identify the cascading effect the following main research question will be answered:

What is the economic impact of larger capacity container ships for feeder operations between the German North Sea ports and feeder destinations in Scandinavia and the Baltic States?

Five sub-questions will be used to answer the main research research question:

- What is the current research regarding the cascading effect and how are choices made for port and ship selection?
- How can the liner shipping network design problem be solved?
- What data is used to solve the liner shipping network design problem?
- How is the optimisation model verified and validated?
- What is the impact of the parameters, bunker costs, total inflow, and minimal port inflow on the choice of feeder container ship?

Current research on the cascading effect and how choices are made regarding port and ship selection is found in Chapter 2. The methodology of the model is presented in Chapter 3, that is required to solve the liner shipping network design problem. The data acquired to solve the problem is presented in Chapter 4. The verification and validation of the model will be presented in Chapter 5. The results of the case studies performed for this thesis are found in Chapter 6. The case studies vary bunker costs, total container inflow, and minimal port inflows. Conclusions and future recommendations are found in Chapter 7. The data used is shown in Appendix A and B. The detailed results of the verification, validation and case studies are found in Appendix C.

2
Literature Review

The review of the available literature shows, the state of the current knowledge and what is deficient, and what can be used as a foundation for this thesis. The problem of the cascading effect is analysed first. Then, the factors for a successful solution of this problem are established, after which a model is required to test the possible solutions. This literature review will look further into the research on the four factors that are regarded important for the goal of this thesis, namely the cascading effect, port choice, route optimisation and route modelling.

In Section 2.1 the problem of the cascading effect of container ships is approached. What the cascading effect means for the use of container ships, new trade lines which ships may find themselves on and how ports can evolve with larger ships in mind. Secondly, in Section 2.2 port choice for container ships will investigated. Ports are an important link in the supply chain for containers. As a potential bottleneck for the supply and demand of containers, a choice in port will influence the path chosen for a container from its origin to its destination, considering the costs that a specific path incurs. Certain ports with a large demand of containers may lack the capabilities to receive the largest ships, making those ships travel further and therefore their cargo also. This has a result in a less efficient and less economical journey for those containers.

Thirdly, and closely aligned with the previous section, in Section 2.3 literature on route optimisation is found. Network design is needed to identify the routes taken by ships which if done well can lead to considerable cost savings for the liner shipping companies. The fourth factor is route modeling and is found in Section 2.4. Optimisation of the supply chain requires modeling to solve for minimisation of the costs. The optimisation of which depends on the type of algorithm used to solve the problem.

2.1. Cascading effect

The cascading effect, according to the ITF, takes place when ship size increases so that other ships become redundant. This occurs when new ULCS and VLCS are deployed on a particular route, smaller ships are deployed to subsequent routes, that in turn leads to a trickle-down-effect on further subsequent routes [5]. For example, ships that are initially deployed on the main East West trade routes rarely spend their entire lifetime on that same trade route. They trickle down to other trade routes when larger ships are deployed on the same route.

The size and capacity of the container liner shipping fleet until 2014 is described by Khoi and Haasis. From the early 80's until 2014 the fleet capacity increased on average 8.3% annually and doubled every decade. It is found that the transportation volume of containers is highly correlated with fleet expansion, however the growth rate of the transportation volume is smaller than the expansion of the fleet [43].

In 2015, the ITF provided three scenarios for the following 5 years. The three scenarios were a baseline where there is a capacity growth in line with market demand in 2020, an addition of 50 container ships with 24,000 TEU capacity, and an addition of 100 container ships with 24,000 TEU capacity on the main Far East - North Europe line. What was seen is that regardless of an increase of the deployment of ULCS, all average ship dimensions will increase for every selected trade route. The ship dimensions calculated as a result of the third scenario are the largest. However this model was run on the assumption that there are no size restrictions in ports on these trade lanes [5].

The ITF notices further that between 2007 and 2014, ships were being redeployed from the Far East-Europe route to the Transpacific route, specifically to the West Coast of North America. A growth of 54% was seen during this period, which is significantly more than between the Far East and the US East Coast due to size restrictions in the Panama Canal [5].

The deployment of a new generation of container ships is largely due to economies of scale that these ships can provide based on the assumption that an adequate utilisation of the larger ships can be achieved, according to Sys et al. The total costs of various sizes of ships were produced by calculating the costs of operations, capital and bunker costs giving the cost per TEU per day of a specific ship size. It is seen that there is an exponential decay of the unit cost per TEU. Furthermore, for ship sizes larger than 9000 TEU costs were calculated for two propeller shafts, which increase the unit cost and diminishes the economy of scale created by the addition of the amount of containers [70].

The ITF points out that the largest ships are primarily designed specifically for the Far East-Europe route. This route is saturated with container traffic, but it is also the route with the longest distance in nautical miles. Most of the economy of scale is created whilst at sea due to fuel cost savings per TEU. Also that in comparison to shorter trips, a smaller proportion of the trip is spent in port where ships are not fulfilling their primary function. The problem that arises here is that cost savings initially attributed to ships are calculated for the entire lifetime of that ship deployed on the same route. If a ship is cascaded down to a shorter route, the cost savings per TEU will diminish as less time is spent at sea [5].

According to Khoi and Haasis, economies of scale have been outweighed by an upswing of oil price and low slot utilisation. Furthermore larger ships suffer a dis-economy of scale whilst in port. This is due to the fact that the time spent in ports is proportional to ship size, extra costs due to a larger size and the large amount of inventory costs accrued by large ships [43]. The point is further continued by showing the considerable investment needed for a reliable weekly service, whereas eight 3500 TEU ships require an investment of $517.7m, eight ships of 12,000 TEU require $1.39b. The investment for larger ships is considerably higher than for smaller ships. Even if the investment per TEU is the same.

As the size of the ships on certain routes changes due to cascading, so will the network configuration. Cariou and Cheaitou investigate the possibility for liner shipping companies to alter their services, such as adding an additional stop at a major hub. Adding a call on the Northern Europe-South America route leads to a potential change in network configuration from direct to indirect services. The additional stop is mainly used by the smaller sized ships and depends on the amount of containers waiting to be collected at the hub. Larger ships are able to minimise the amount of port calls they make [26].

This preference to minimise the port calls for larger ships will mean that a smaller group of ports will cover a larger hinterland per port. As a consequence the number of transshipment and feeder activities will have to increase to be able to satisfy the demand of various regions further removed from the larger ports. A way to get around this is to implement secondary hubs into the transportation chain. Monios et al. look into the implementation of such hubs, which have the capacity to receive large ships, and have adequate in-land links and be in the vicinity of a cluster of small ports. The implementation of which could mean that cascaded large ships have a place in the market to operate between main hubs and secondary hubs, considering there is a large local captive market and an aggregated demand from local small ports. For example: if the port can handle vessels up to 3500 TEU, it could accommodate some feeder vessels that may cascade down once larger vessels enter service on the mainlines, making it well-placed to compete for feeder cargo across the north of the U.K. [55]. Furthermore, according to Monios et al., until excess capacity is removed from the system and unless carriers retreat from the current strategy of ever-larger vessels and the cascading effects that result, such a hierarchical network will be necessary [55]. Problems facing small ports are further elaborated by Monios. Possible solutions are given, such as upgrade to become a secondary port or merge with other nearby small ports. Small ports with relatively captive local markets are likely to survive, but the price of staying in the service of a less economic vessel may become too large. If this is the case, the port may have to invest in berth and channel dredging for larger ships to enter [54].

From what it is seen from the literature on the cascading effect is that it is considered to be inevitable. Container ships are constantly being superseded by larger container ships which were previously thought to be too large to even exist, be it either because of size restrictions in ports or on the routes, or because there is not enough freight to be transported. However what was the largest ship 15 years ago, has now around half of the capacity of the largest today. Companies are worried that they will be left out if they do not order larger ships themselves, so the amount of the ultra large container ships grows.

Where one ship is built for an increase in the economy of scale gained, another looses it in what is a dis-economy of scale. The old ship is too large for its new route, but there are ways around this. New ports added onto traditional routes may add container flows to certain routes which were not possible before due to ship capacities being full. Another way is to add a new layer of transshipment into the hub-and-spoke-network, which adds new transshipment hubs nearer to the small destination ports, or even to merge nearby small ports into larger hubs. Although the latter is not applicable for ports which are in cut-off regions.

2.2. Port choice

To be able to make a selection of ports for consideration as destinations of feeder services, it has to be understood why certain ports are chosen. The decision makers may not be so apparent. Are liner shipping companies the decision makers? Or are their decisions made for them by port authorities, or by other factors beyond their control? This part will follow literature on port choice. Firstly, means of gathering port choice preferences will be presented. Secondly, the factors where decisions are based on will be shown. Finally, port evolution from the past 50 years is shown, and how port evolution has changed port choice.

Early studies on port choice were based upon surveys taken by shipping companies such as by Slack, who states that decision makers are more influenced by price and service considerations of land and ocean carriers [68]. D'este and Meyrick state that conservative decision makers have an emphasis within price bounds, to quality of service, particularly on speed and reliability [34], and Murphy and Daley state that shipment information and loss and damage performance are the most important factors in selecting water ports [59].

Later studies have looked into the use of Analytical Hierarchy Process (AHP) to analyse the data retrieved from surveys. Lirn et al. use AHP to reveal transshipment port selection by liner shipping companies. It is found that the 5 most important service attributes of transshipment ports are: handling cost, proximity to main navigation routes, proximity to import/export areas, infrastructure condition, and feeder network [48]. Chou utilises AHP to simulate the behaviours of carrier's port choice and identifying the weights of factors influencing port choices in multiple-port regions. Two conclusions are made. For oceangoing carriers the main concerns are depth of the container ship berth, port charge, tax, rent and cost, and port loading/efficiency. The coastal carriers have similar concerns: hinterland economy, port charges, tax, rent and cost, and port loading/discharging efficiency [29].

Another study, by Chang et al., uses AHP to determine important attributes for trunk liners and feeder service providers. The feeders in question are providing a service for intra-Asian trade. The conclusion made from this paper is that feeder liners assign more importance to the operation condition of shipping lines and marketability. Furthermore, main haul liners face more competition which requires them to provide a more value-added service than feeder liners do. Main haul shipping liners are more sensitive to port costs than feeder service providers [27].

Other ways to analyse the choices made by liner shipping companies is to use multinomial logit programming (MLP). These models can assign attribute weights to parameters to predict future choices based on previous choices. Mueller et al. use MLP to analyse 31 European ports on deep sea connections, on terminal selection inside ports, port hinterland strategies, hinterland corridor efficiency, and inland port operations. The five significant port choice factors were hinterland transport costs, maritime transport costs, hinterland transport time, number of port calls and a negative dummy variable for rail transport. Oil prices was chosen to show the application and sensitivity of the model. Variation of which lead to a change in modal split. An increase in oil price will see less road transport, and more transported by rail and inland water transport (IWT). Furthermore, the average hinterland road transport distance decreases, whilst demand per region is kept. A conclusion here is that higher oil prices lead to a port choice that is closer to the final destination of the container. Rail and IWT are less dependant on oil, and see less variation of use and distance when oil price increases [56]. A similar conclusion was made by Veldman et al. A multinomial logit model was used to determine the factors of port choice in Spain. The factors included inland transit cost, ocean transport costs and a variety of variables for quality of service. The authors found that for Spanish ports inland costs had a higher impact on port choice than ocean transport costs [75].

The use of discrete choice analysis in the form of MLP should be given a higher weight than AHP in regarding the outcomes of the above studies. The use of AHP requires tradeoffs and pairwise comparisons so experts can value criteria and alternatives. By doing so, the valuation leads to inaccurate responses since it is has been established that people have difficulty explaining why they make certain decisions. It is further known that people are able to make good decisions between alternatives [61]. Therefore the conclusions from the papers using MLP should be given more weight into what is important for port choice. This means that the hinterland transport cost is one of the most important factors that will be taken into consideration. However, other factors which where seen to be significant in their respective studies will be taken into account. To mitigate the hinterland transport cost, a solution is to decentralise the throughput of containers by setting up secondary ports in the middle of the chain. These ports are large enough to handle both gateway and transshipment traffic. These are so-called second-tier ports which have been inserting themselves between hubs and feeder ports [55].

According to Khoi and Haasis, port choice is related to market coverage. Whereas the more ports are visited, the closer a service is to customers. The amount of ports added to a route determines the voyage distance therefore port choice is closely correlated to the final network design [43].

Tang et al. have developed a Network-based Integrated Choice Evaluation which identifies important quality characteristics on which liner shipping companies can base their port choices. An empirical study of Asian ports was made, that takes the following into account: port traffic (TEUs), port calls, annual operating hours, draught, inter-modal transport, trade volume, port charges, and ship turnaround time. Results show that there is a trend that shipping alliances choose to call at fewer ports with efficient services, provided scale economies can be achieved [72].

Martínez et al. make the definition of factors under control of port authorities and factors beyond control. Factors under control are where port authorities have the ability to influence by means of policies. These are namely port performance, port connectivity and port charges. Factors beyond control of port authorities are port location, transport costs, port efficiency and quality of port services [49].

Monios et al. conclude that key factors for the development of second-tier ports include having a cluster of small ports within minimal sailing distance, suitable channel and berth depth in the port, handling facilities for the increased demand, and high capacity inland links. Secondly, due to the aggregated demand of the small ports, a large local captive market can be realised, as well as increased overland servicing of these smaller ports. For the container ships themselves, ULCSs can service the gateway hubs, whilst the ships that are replaced by the ULCSs can be put into service between the gateway ports and the second-tier ports [55].

Several papers have followed the evolution of port systems from the early 1980's until the present day. Hayut describes a five phase model that follows the concentration of container flows from a static equilibrium to development of the port and concentration of container flow to a point where smaller ports challenge the larger port for a larger stake in container traffic [39].

The larger stake in container traffic proposed by Hayut was explained by dis-economies of scale and congestion within container terminals. However this is not necessarily the outcome for all container terminals. A case study performed in 2002 of three Asian main ports pointed out that in the case of Hong Kong and Singapore, neither suffered major inefficiencies in their terminals. Peripheral port challenges come from institutional factors, being it from terminal operators creating new terminals in the vicinity, or the desire of major shipping lines to manage their own container terminal as such is the case in Singapore [69].

Decentralisation seems not to be the final step in the evolution of the port system. Notteboom and Rodrigue add the regionalisation phase, which comes after the decentralisation and insertion of an offshore hub phase. Where inland distribution becomes a cornerstone in port competitiveness [62].

However, ports within the same region may not be competing with another. Adolf Ng assesses the attractiveness of North European gateway hubs by handing out a Likert-style questionnaire to employees of the top 30 shipping liner companies representing 80% of the global market shares. On average, the Benelux and German ports score higher than Felixstowe and Le-Havre. The German ports of Bremerhaven and Hamburg are prefered for transshipment to Scandanavian and Baltic ports, whilst Antwerp, Felixstowe, Le-Havre and Rotterdam are better placed for transshipment for the UK and Iberian Peninsula [18].

Gouvernal et al. researched the port system evolution in the western Mediterranean. Due to growth in the throughput of containers in ports in the Mediterranean, the distinctions between gateway and transshipment ports blur. So much that gateway ports on the south European coast are attracting more transshipment cargo to become hybrid ports. These ports are continuing to serve the local markets, as well as regional markets. These ports are finding it difficult to push their hinterlands further than the Alps and the Pyrenees because of the connectivity and service of the North-European ports [38].

Wilmsmeier and Monios analysed the port system in the United Kingdom between 2005 and 2010. It was observed that there was a shift from the South-East being the traditional gateway area for UK destined cargo, to transshipment of containers from mainland European ports. The choice of a particular regional port depends on the land available and the quality of the hinterland connections. Most of these ports offer uncongested handling facilities and cheap brownfield land for development, however the inland transport links tend to be of a lesser quality than with large ports. Due to the increase of vessel size on main line routes, and the following cascading of vessels, it is expected that ships in the 2000-4000 TEU range will serve regional ports. Not every port has the handling facilities to handle a larger size ship, which leads to a shift to hybrid ports and the use of smaller feeders or land transport for transshipment from the second-tier ports [77].

It is shown from these papers that port choice varies from who is asked. Also on how their preferences are deduced, be it from asking them directly or by varying attributes for each choice they make. According to questionnaires using multinomial logit, the most significant attribute for short sea port choices was hinterland costs. Port evolution shows that there is a process of container flow concentration to deconcentration and regionalisation, which allows for smaller ports in the vicinity of gateway ports to attract more containers for their own transshipment. This allows for a reduction of hinterland costs, whilst using the economy of scale gained by utilising larger capacity container ships for as long as possible.

2.3. Route optimisation

An overview of the current knowledge of network design is given by Christiansen et al. The containerised liner shipping network design problem is defined as followed: Given a collection of ports, a fleet of container vessels and a group of origin-destination demands, a set of services is constructed for the container vessel such that the overall operational expenses are minimised, whilst ensuring that all demands can be routed through the resulting network from their origin to their destination, respecting the capacity of the vessels. Four constraints of the problem are presented. These are: transit time, transshipment costs, rejected demands and speed optimisation. Four types of service routes are also presented for European ports. These are: 'simple service' where each port is visited once, 'butterfly service' where one port is visited several times during a service, 'pendulum service' where all ports are visited twice in both directions, and 'complex service' where a butterfly node is visited multiple times [32].

Christiansen et al. wrote a review on the status and perspectives of ship routing and scheduling. A multitude of research papers are presented on various subjects within the routing and scheduling from the years leading up to the turn of the 21st century. Furthermore, the perspectives of the authors are given, where it is foreseen that more integration along the supply chains will become increasingly important [30].

An update of the review in 2004 was presented by Christiansen et al. Papers written between 2004 and 2013 can be grouped up into four categories:

- Models with a single route or set of routes without transshipment.
- Hub and feeder route models where each feeder port is connected to a single hub port.
- Models where some ports are classified as hub ports without any constraints on the number of hub and non-hub ports a route may visit.
- Multi route models without any separation of hub and non-hub ports [31].

Takano and Arai present a genetic algorithm for the hub and spoke problem for a fixed number of hubs to determine the best network configuration and to minimise the total costs of the system. It also offers the ability to trade between hubs, whilst every feeder port is only linked with one hub. The results show that a shorter distance between hub and feeder port does not necessarily mean that a link will be made between the two, as in some cases it is more economic to transfer the cargo flow to another hub port with links not operating at full capacity, than to add additional ships to existing links to satisfy the demand of container transport [71].

Meng and Wang present a model for an intermodal hub and spoke network for multi-type containers. A hybrid genetic algorithm is used where they penalize violation of capacity and costs for changing over from transport type. The case presented in the paper is that of the region north of Singapore with road, rail and sea links [52].

Meng and Wang further present a liner shipping service network design with combined hub and spoke and multi-port-calling and empty container repositioning. The novelty here is that transshipment is only allowed in some hubs, making sure that each feeder port is assigned to one hub port, whereas most of the predefined routes visit several hubs and feeder ports. To keep the amount of possible routes down, each container is only allowed to be at most transshipped twice between any two ports [51].

Gelareh and Pisinger present a simultaneous fleet deployment and network design model. This uses Mixed Integer linear Programming (MIP) to simulate a cyclic route in a region of service passing through a set of designated hub ports, such that the remaining feeder ports send their demands using feeder vessels to a finite and limited number of ports on the circular route [37].

Reinhardt and Pisinger formulate a branch-and-cut model which includes the possibility to use butterfly routes, as well as transshipment costs in the objective function and the calculated time in the routes created [67].

Medbøen et al. look into the design of a robust short-sea feeder network for Norwegian ports, explicitly accounting for the effect of uncertain travel times caused by harsh weather conditions. The results show that weather uncertainty can severely impact the synchronization of the routes and should be taken into account in the design phase of the logistics system. The optimization-simulation approach, especially when using different performance-improving strategies, finds robust solutions at only a small operational cost increase. When an optimal route has been established, it is beneficial if it can withstand external factors. Establishing a new route for multiple ships which are deployed for a weekly schedule can be a costly affair as well as taking up time [50].

Cheng and Wang have tackled the network design problem by taking the shipper's dual preference into consideration. The dual preferences meant here are the seasonal fluctuations in shipping demand and shipper's inertial preference (i.e. time preference and freight rate preference) [28].

There are various types of methods that can be used for creating routes. These are simple, pendulum, butterfly and complex. Whereas a choice of one depends on a multitude of reasons but not limited to, from ship size and amount used for the service, the flow of containers, port size and distance between ports. Choices can also be made to move transshipment of containers from ports to offshore nearby which have less size restrictions, but could cost more to move containers from ship to ship.

2.4. Route modelling

Closely following the network design are the types of algorithms used to model the networks. As well as presenting types of network design, Christiansen et al. present four widely used algorithm types and papers written with one of the algorithm types. The 4 categories are: mixed integer programming (MIP), two-stage algorithms, subset of routes, and backbone flow. MIP algorithms use an MIP model which designs the services and flows of containers for a network. To achieve this, two sets of variables are required. One set being the one which selects arcs in a service, and the other is to denote the flow on each arc. Several papers Christiansen et al. mention are: [20], [67], [65], [64] and [76]. Two-stage algorithms use two steps to solve the liner shipping network design problem by designing the services and then the flow of containers through the resulting network. Papers mentioned by Christiansen et al. are: [19], [20], [23], [22], [58], [41], [73] and [60]. Subset of routes algorithms use existing planners to design multiple candidate services. The algorithm then uses this subset of routes to form a network. This is particularly useful for shipping companies who do not necessarily want the network to be altered beyond recognition, so that not all of their services have to be altered. Small variations to their existing services can be realised by using this algorithm. Two papers mentioned by Christiansen et al. are: [51] and [21], which both provide heuristics for generating candidate services. The final type of algorithm is backbone flow. This approach reverses the steps taken in the subset of routes, so to set out a flow of containers through all possible connections. Connections are priced so that at low loads they are expensive and at high loads they are cheap, so cargo gathers at few connections. The paper mentioned by Christiansen et al. is [45].

Agarwal and Ergun present a model for simultaneous ship scheduling and cargo routing, whilst taking transshipment of cargo into account but not the cost of transshipment. Three algorithms are used to solve the mixed integer problem (MIP). These are the greedy algorithm, pure column generation based-algorithm, and Bender's decomposition-based algorithm [19].

Álvarez uses MIP for joint routing and the deployment of a fleet of container vessels. To solve the MIP, an initial number of vessels are deployed for certain runs. The utilisation of these ships is checked for every time step, whereas an under utilisation of the run will lead to less ships put into service and vice versa. This model allows for different vessel sizes with their representative costs and operation properties, transshipment hubs and transshipment costs, port delays, regional trade imbalances, and the possibility of rejecting transportation demand [20].

Reinhardt and Pisinger use the 'Big M' method in their MIP model. The big M is a constant which helps with keeping the constraints in place. Furthermore to help solve the MIP problem, a branch and cut approach was followed as it seemed that only using the big M method, optimisation of the model may take too long. To help with the formation of butterfly routes, transshipment cuts and connectivity cuts are made. These are made when their corresponding constraints are violated [67].

A benchmark suite for liner shipping network design was formulated by Brouer et al. based on the model found in [20]. This benchmark suite (LINER-LIB 12) functions as a base for future network design and fleet deployment at a strategic level. Results of the various scenarios can be found online, as well as the input data and the model used. The test case of the Baltic shows a fast convergence of the solution, which is due to simplification of the feeder network with only 12 ports and 6 ship sizes included in the model [22].

Brouer et al. propose a matheuristic approach consisting of four algorithmic elements. Those being a construction heuristic, an improvement heuristic, a reinsertion heuristic and a perturbation heuristic. Tests are carried out using these heuristics, where for each test another heuristic was added. A combination of all four of them seems to find the best solution for the cases tested for by Brouer et al. [23]. Mulder and Dekker aggregate ports into clusters based on geographical location. When the routes and flows have been created for the clusters, these are then taken apart for feeder services to be created [58]. Wang and Meng set out to solve the liner shipping network design problem with added transit time and container handling time constraints in a non-linear, non-convex MIP formulation. This is done by using a column generation based heuristic method. The use of this method generates only about 3% of the possible routes generated by the exact model, but offers the same profit for less CPU run time [76]. A follow-on from the model and algorithm used by Brouer et al. is presented by Karsten et al. Constraints are added so that the model will consider the transit time of the existing cargo flow when removing and inserting port calls in the service [41].

A compact formulation of the network design problem based on service flows is presented by Plum et al.. Where previous models had difficulty with recurring port calls on the arc flow, this model addresses this problem by adding service nodes and port nodes, as well as numbering the arcs between a port and a service node. This model allows for multiple butterfly port calls in a route. This is beneficial because there will be an increased capacity on the legs between butterfly port calls as the service will carry less cargo between the two ports; two services with non-weekly frequency can be combined to a weekly service. Draft limits at later ports may require vessels to be eased before port call which a butterfly port can alleviate, and multiple butterfly port calls will improve transit time as an extra port call will allow for faster imports or exports to remaining ports on the service [65].

Thun et al. analyse the effect of different structures of services by proposing a model which has no limitations for the amount of times a port can be entered. The structures being a simple cycle, a butterfly service where one port can be entered twice and a butterfly service where every port can be entered twice. This model is solved by a branch-and-price method, and shows that where every port can function as a butterfly call more cost-efficient networks can be created [73].

Just as Bender's decomposition was used by Agarwal and Ergun, Neamatian Monemi and Gelareh used it to approach the problem of a simultaneous network design, flow and fleet deployment problem whilst taking the repositioning of empty containers into account [60].

Krogsgaard et al. present a model which allocates the container flow first, before designing a service to match the flows. After the initial network has been designed, it is improved by means of a variable neighbourhood search method by inserting a port, omitting a service, service an unused port, remove a port from a service, a simple port removal and create a feeder rotation. The difference of the two port removals is defined by the amount of containers loaded, unloaded and transshipped for the removal of a port, and only loaded and unloaded for a simple port removal. Furthermore, a Lagrange heuristic is used to relax the capacity constraints of the container flow optimisation. However, the solution found by the Lagrange heuristic is found to be 2% to 5% off from the optimal solution [45].

Various types of algorithms are used to solve the liner shipping fleet deployment problem. Ranging from the exact answer to using corner cutting measures to reduce the time needed to solve the problem. There are also different ways of letting the model run by selecting what is to be optimised first. With that knowledge, although a MIP model is simple in use and will lead to a definite answer, it is most likely that the answer will take too long to calculate for a system of ports and vessels. Using 'subset of routes' models is less likely to be chosen due to no prior optimised design. However, a simple design can be made for a backbone flow model, that is then optimised by the algorithm used. Furthermore, it requires container flows beforehand to set up a solution, of which data is readily available. Furthermore, it is understood that most, if not all, models and algorithms presented here do not use a commercial solver, but have an inbuilt solver which out-performs commercial solvers. Depending on the runtime of the calculation, a solver could be made based on one of the solvers presented here.

2.5. Conclusion

The literature review has touched on four different, but closely aligned, factors regarding the deployment of different size of container ships in the North Sea and Baltic Sea. Be it from larger container ships being more prevalent on routes previously sailed on by smaller ships, how ports are chosen to sail to, optimising the routes taken and modelling those routes to see if they are possible for ships in use. The model to be constructed needs to take all of these factors into account and use them to simultaneously solve the intended formulated optimisation equation.

From what is seen in the literature is that a shift is being seen where ships which were previously too large for certain routes, are being put onto these routes. As a consequence, ports in Northern Europe with small container inflows will have to be upgraded or lose out to other ports in their vicinity. Furthermore, routes to ports are placed based on their vicinity to population hubs and the demand of those population hubs.

Ports within the region can be put onto butterfly routes, which would allow for large ships to service multiple sub-regions of ports. To come to a conclusion on the use of larger capacity container ships, a liner shipping network design problem needs to be solved. This will be done for multiple capacities of ships, so to identify the impact of larger capacity ships on the total cost of moving all containers from the origin to the chosen destinations. A complex system of ports and routes will require a specialised optimisation algorithm. However, it is assumed that a commercial MIP program will be able to find a optimal solution as long as the amount of variables remains small enough for it to handle. The MIP program will be based on an optimisation model shown by Christiansen et al., which uses arc formulation for the liner shipping network design problem. To determine if the cascading effect will be noticed in the North Sea and Baltic Sea region, a change in choice of container ship capacity will be seen in varying the bunker cost and the container flows. The latter can be split up in to increasing the container inflows of all ports at the same rate, and reducing the amount of feeder destinations based on the amount of container inflow per port. These will test the economy of scale of ships with a larger capacity.

3
Methodology

This chapter describes the methodology used in the thesis. The goal of this thesis is to investigate the cascading effect of container ships on the choice of feeder ships between European gateway ports and feeder ports in Scandinavian countries and countries on the Baltic Sea. To achieve this goal, costs are calculated for the distribution of containers from a major port to feeder destinations for various ship sizes based on voyage costs, capital costs, and operating costs. To come to a conclusion about the choice of feeder ships in the North Sea and Baltic Sea region, a mathematical model is created to solve the liner shipping network design problem in the area. Models of this kind are used to assign vessels to container flows or vice versa. In this case, a model is used to assign types of vessels between the feeder hub (origin) and the destination port for given container inflows between the origin and demand ports. The model created for this thesis is based on the 'arc formulation for liner shipping network design problem' presented by Christiansen et al. [32].

3.1. Scope of the model

Each origin-destination (OD) pair has a container flow, which is determined beforehand. From these container flows, vessels can be assigned to arcs so that the container flows are fulfilled. The two are linked with each other. Once a set of flows of containers and vessels is determined, the set can be tested for restrictions.

These restrictions curtail the capacities of the ship and the size restrictions of ships in the Kiel Canal. Ship capacities are used to divide the container flows into chunks which are then moved together across an arc. The quantity of these groups of containers are equal to the number of trips required to ferry them. The added variable of trips required to move the containers makes the distinction possible between the voyage costs, compared to the operating costs and capital costs.

Due to the size restrictions of the Kiel Canal, certain ships are not able to enter it. As a result, ships which are larger than permitted have to sail around the tip of Denmark. This means that arcs between major ports and ports on the Baltic Sea will have significantly longer distances than if the arc would pass through the Canal. Arcs passing through the Canal will have the same OD-pair as an arc not passing through the Canal. Adding both OD-pairs with the same 'name' with different distances and costs, will incur faults within the model. It is therefore chosen to generate two separate sets of arcs, one which will pass through the Kiel Canal and one which does not pass through the Canal. This means that the model proposed is incapable of choosing ships from a list provided to it.

Once the set of flows has passed the restrictions, the model should look to the least total cost of the sets. These costs are divided into two main groups, fixed costs and variable costs. Fixed costs are mostly dependant on the capital and operating costs of the ships. Variable costs are dependant on the arcs chosen for vessels. The length of an arc determines fuel cost (assuming a set speed), but also the time spent in port. Time spent in port includes time spent maneuvering, unloading cargo and taking on supplies or other cargo. Once all costs are totaled up, the model will come to the conclusion if a lower cost can be achieved for a different set of flows or not.

A more detailed explanation of the model will be explained further in this chapter. The equations of the model are presented in Section 3.2. The complete model and its explanations are found in Section 3.3. This includes all parameters, variables and constraints used. The objective function is also found in this section.

3.2. Equations used in the model

This section will be split up just as the model is presented in Figure 3.1. Firstly, the equations used for the determination of container and ship flows are presented. Secondly, the way ship capacity and canal restrictions are implemented into the model are shown. Finally, the objective function and the equations required to calculate the various costs are presented. Assumptions made for the equations are also given in this section.

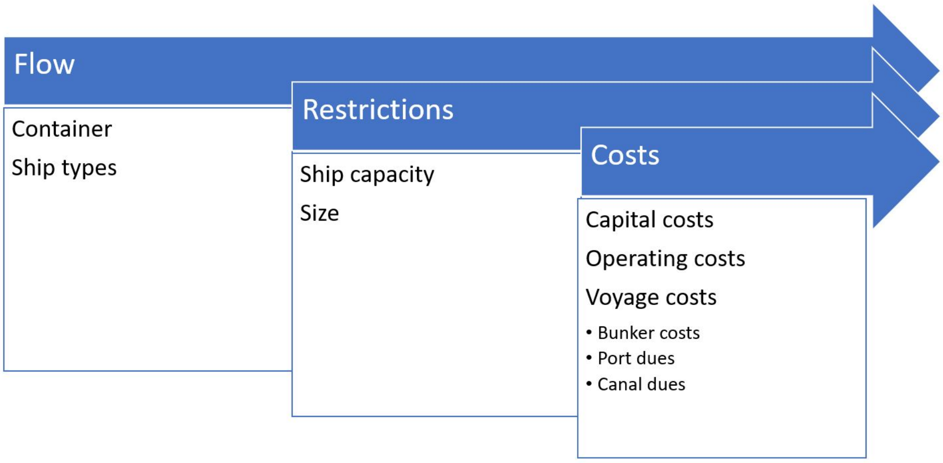


Figure 3.1: Abstract of model

3.2.1. Flow

The flows of the model are split up into flows of containers and flows of ship trips, situated on arcs A between ports $(i, j) \in A$, by ship type $v \in V$. Flows of containers $x^v_{i,j}$ are determined beforehand, therefore it is chosen that there is no rejection of containers and flows cannot be negative. It is possible for containers to enter a node, and leave it if the node is not the destination of the containers. The difference between the flow of containers and the inflow into a node IF_j equals the containers which have entered the node and leave it. This is reflected in equations 3.1 and 3.2. The above will restrict ship's trips, but will ensure that demand of containers is satisfied. Furthermore, it is to be noted that whenever containers are chosen to flow along an arc, there must be at minimum one trip undertaken by a ship on the same arc $tr^v_{i,j}$ of which the capacity of those ships SZ^v is not exceeded by the flow of containers on that arc. This is reflected by equation 3.3. To mitigate transshipment on a route, the number of trips entering a node is made equal to the trips leaving that node. This is reflected by equation 3.4 using the integer parameter $tr^v_{i,j}$. This also ensures that ships return to the original node when the demand of all other nodes is satisfied. The flow constraints of the containers and trips will allow for transshipment between ships of the same ship type. The above results in the following equations for the container flow and ship inflow:

$$\sum_{j:(i,j)\in A} \sum_{v\in V} x^v_{i,j} - \sum_{j:(j,i)\in A} \sum_{v\in V} x^v_{j,i} = IF_j \forall i \in N \tag{3.1}$$

$$\sum_{(i,j)\in A} x^v_{i,j} \geq 0 \forall v \in V \tag{3.2}$$

$$tr^v_{i,j} * SZ^v \geq x^v_{i,j} \forall (i,j) \in A, v \in V \tag{3.3}$$

$$\sum_{j:(i,j)\in A} \sum_{v\in V} tr^v_{i,j} - \sum_{j:(j,i)\in A} \sum_{v\in V} tr^v_{j,i} = 0 \forall i \in N \tag{3.4}$$

3.2.2. Restrictions

The restrictions taken in to account for the model are size restrictions as a result of the Kiel Canal, and capacity restrictions of ships deployed on arcs. The ship capacities have already been mentioned in Subsection 3.2.1 in equation 3.3. The capacities are required to calculate how many times a ship must travel along an arc, for the amount of containers being moved along that arc. The unit of the ship capacity is to be in TEU. If there is a case of larger containers being used, the equivalent amount in TEU will be calculated. Similarly, in the case of the transit of reefers, these will be seen as TEU for this thesis.

In the region covered, the only canal is the Kiel Canal. This thesis does not take other canals into account which are used for inland shipping, nor canals which have to be navigated to reach certain ports. The latter are taken into account for distances to and from the ports. The Kiel Canal connects German North Sea ports and Dutch ports with ports situated on the Baltic Sea and Gulfs connecting to it. It is understood that the the Kiel Canal has size limitations that have an effect on the ships looked into for this thesis. To incorporate the Kiel Canal into the model, a separation in sets of arcs is made. One for ships small enough to sail through the canal, and one for ships too large.

The assumption is made that, given the choice between sailing through the canal or to sail around the northern tip of Denmark, a ship will choose the shortest distance. Regardless of extra canal duties occurred by taking the shorter route through the canal. This is as long as that ship can enter the canal. For the ships too large for the canal, the longer distance is used. The reason why this distinction is made, is that both OD-pairs (one using the canal, and one not) will have the same two nodes. It will be then too difficult to have both OD-pairs in the model, where one has to pay dues for using the canal, and the other not.

3.2.3. Costs

The objective of the model is to minimise the total costs of of a container ship to fulfill the inflow of all ports chosen. The costs are to be split into three parts: operating costs, capital costs, and voyage costs such as described by Van Hassel et al. [74]. Operating costs and capital costs are calculated for the total time spent by a ship type whilst in use. Voyage costs are calculated for each time an arc is used by a ship type, and consists of: fuel costs at sea $FCS^v_{i,j}$, port costs PC^v_j and canal costs $CaC^v_{i,j}$. Equation 3.5 shows the objective function used in this model.

$$min \sum_{v \in V} W^v * (CC^v + OC^v) * ti^v + \sum_{vin \in V} \sum_{(i,j) \in A} tr^v_{i,j} * (FCS^v_{i,j} + PC^v_j + CaC^v_{i,j}) \tag{3.5}$$

Operating costs and capital costs are taken from Mulder [57]. Mulder approximates operating and capital costs based on service during a whole year. Van Hassel approximates costs based on the actual time spent in operation. It is chosen to follow the calculation of VanHassel2016 of operating costs and capital costs, paid per hour a ship spends in operation. Capital costs CC^v include the depreciation of the ship, based on the purchase price. Operating costs OC^v take the crew wages, maintenance, repairs into account.

To calculate the total capital and operating costs of a particular ship type during its feeder operation, capital and operating costs per hour are multiplied by the number of hours spent completing all container flows between the origin and destinations. Feeder services in the region, such as presented in Appendix A, are generally completed within a week, so to fulfill weekly container demand. However, a constraint of weekly services is difficult to create. If the voyage takes longer than a week, it is assumed that a different ship will set sail before the ship of the previous week has returned. To satisfy this constraint of weekly services, it is chosen to use one ship per time, of which the time required to fulfill all flows is calculated. For example, doubling the quantity of ships used of a particular type, will only cut the time spent in half, but will double the capital and operating costs of that ship type. This results in no difference in total cost. However, to make sure that the model does not increase the amount of ships allowed in the model at the same time, Equation 3.6 is included. Herein W^v is the amount of ships used, and M^v is max permitted ships in the system. W^v is included as a variable.

To ensure that W^v is a positive integer, Equation 3.7 is introduced. Herein the time spent is calculated per ship in the model. Time is calculated for each time a ship enters a port Tp_j^v, and for the time spent sailing between nodes. Time spent sailing between nodes is calculated by dividing the distance between nodes S_i, j by the sailing speed of the ship in question Vc^v. Time spent at sea and in port is multiplied by the number of trips made on the arc connecting two nodes by a ship $tr_{i,j}^v$. The total time spent by a ship ti^v is calculated by summing the hours spent sailing on all arcs and nodes used by a ship, and multiplying this by the number of ships W^v included by the model.

$$\sum_{v \in V} W^v \leq M^v \tag{3.6}$$

$$\sum_{(i,j) \in A} \sum_{v \in V} (Tp_j^v + \frac{S_{i,j} * 1.852}{Vc^v}) * tr_{i,j}^v = ti^v * W^v \forall v \in V \tag{3.7}$$

Voyage costs, according to Van Hassel et al., are mainly based on the fuel consumption and lubrication consumption during the voyage of the vessel, and port dues and canal dues incurred during voyage. Voyage fuel costs are calculated by multiplying the bunker cost BC by the specific fuel consumption of the ship whilst sailing $SFCS^v$, the brake horsepower of the ship Pb^v, and the length of the arc $S_{i,j}$ divided by the speed of the vessel. The units used in the equations are: dollar per kilogram, kilogram per kilowatt hour, kilowatt, kilometers and kilometers per hour respectively. Note that the voyage costs are calculated for each time a ship utilises an arc, so will be multiplied by the number of trips made on the arc for the total costs. The equation for the voyage costs is seen in equation 3.8.

Port and canal dues are included in the total cost. Equation 3.10 shows the canal costs CaC_j^v. These are to be added to arcs where ships utilise the Kiel Canal. These ships will have different arc distances to ports East of the Kiel Canal. Canal costs are based on the GT of a ship. An array $SCD_{i,j}$ consisting of 1s and 0s is used, where an arc which uses the canal is denoted by a 1, and an arc which does not use the canal is denoted by a 0. This array is multiplied by a canal due $CD_{i,j}$, predetermined beforehand and dependent on the size of the ship traversing the canal. Port costs PC_j^v are split up into two groups. The cost of entering a port PD_j^v, and fuel cost BC in port. Port entering costs are based on the gross tonnage of the vessel entering the port. Fuel costs in port are based on fuel consumption whilst operating in port. The fuel consumption is therefore also dependant on the time spent within the port. Furthermore, the various port costs depend on the number of times a ship enters the port, which is denoted by the amount of trips a ship makes on an arc. Equation 3.9 shows how the costs are calculated. All of the costs above are dependant on the number of ships they apply to. Note that for ports within the region, none use the same currency as is used for bunker costs, so an exchange rate (xrate) is used, to convert the canal and port dues into dollars.

$$VC_{i,j}^v = BC * Pb^v * \frac{S_{i,j} * 1.852}{Vc^v} * SFCS_v \forall (i,j) \in A, v \in V \tag{3.8}$$

$$PC_j^v = BC * Pb^v * Tpmin^j * SFCP^v + xrate * GT^v * PD_j^v \forall j \in N, v \in V \tag{3.9}$$

$$CaC_{i,j}^v = SCD_v * CD_{i,j} * xrate \quad \forall v \in V, (i,j) \in A \tag{3.10}$$

General liner container shipping network design models make use of services that the vessels used in the model are bound by. A service is a set route that stops at designated ports and ends in the port of which it started. These services are either generated beforehand or are generated in conjunction with the assignment of the fleet and flows of containers. To ensure that the model used in this thesis has complete freedom to assign ships to flows of containers, no services are used. The implementation of services forces ships to be used for multiple ports where they may not be the best suited for. For calculating the flows and the corresponding vessels, an extra degree of freedom of choice allows ships to be sent to a singular port and then return to the origin. A complete version of the mathematical model is seen in Section 3.3.

3.3. Mathematical model

The parameters of the model are split up into three groups for legibility and are as follows:
Port and arc parameters:

- N is the set of ports in the system, that are the main ports in their respective clusters
- A is the set of arcs that connect two different ports i and j
- S_{ij} is the distance between two ports along arc i, j in kilometers
- IF_j is the inflow of containers to and from ports

Ship parameters:

- V is the set of the chosen container ship sizes
- M^v is the quantity of each container ship types allowed in the model
- Pb^v is the brake horsepower of each container ship size, calculated separately [kWh]
- $SFCS^v$ is the specific fuel consumption of each container ship size whilst at sea [kg/kWh]
- $SFCP^v$ is the specific fuel consumption of each container ship type whilst in port [kg/kWh]
- SZ^v is the container capacity of each container ship type [TEU]
- Vc^v is the ship velocity for each container ship type [km/h]

Costs and miscellaneous parameters:

- CC^v is the capital costs for each container ship size per hour [$/h]
- OC^v is the operating costs for each container ship size per hour [$/h]
- $VC^v_{i,j}$ is the voyage costs for each container ship size sailing on arc (i, j) [$]
- PC^v_j is the port cost for ships entering a port [$]
- CaC^v_j is the canal dues for ships entering a canal [$]
- BC is the bunker price used for the ships [$/kg]
- $Tpmin_j$ is the minimal time spent in ports by vessels [h]
- $xrate$ is the exchange rate for Euros to Dollars [€/$]

The variables used in the model are as followed:

- W^v is the amount of vessels used per ship type
- $x^v_{i,j}$ is the amount of containers flowing on arc (i, j) in container ship size v [TEU]
- $tr^v_{i,j}$ is the amount of trips undertaken by a ship type on an arc (i, j)
- ti^v is the amount of time a ship type is used in total [h]

This gives the following objective function and the following constraints:

$$min \sum_{v \in V} W^v * (CC^v + OC^v) * ti^v + \sum_{v in \in V} \sum_{(i,j) \in A} ti^v_{i,j} * (VC^v_{i,j} + PC^v_j + CaC^v_{i,j}) \tag{3.11}$$

$$\sum_{(i,j)\in A} x^v_{i,j} \geq 0 \forall v \in V \tag{3.12}$$

$$\sum_{j:(i,j)\in A} \sum_{v\in V} x^v_{i,j} - \sum_{j:(j,i)\in A} \sum_{v\in V} x^v_{j,i} = IF_j \forall i \in N \tag{3.13}$$

$$\sum_{j:(i,j)\in A} \sum_{v\in V} tr^v_{i,j} - \sum_{j:(j,i)\in A} \sum_{v\in V} tr^v_{j,i} = 0 \forall i \in N \tag{3.14}$$

$$tr^v_{i,j} * SZ^v \geq x^v_{i,j} \forall (i,j) \in A, v \in V \tag{3.15}$$

$$\sum_{v\in V} W^v \leq M^v \tag{3.16}$$

$$\sum_{(i,j)\in A} \sum_{v\in V} (Tp^v_j + \frac{S_{i,j} * 1.852}{Vc^v}) * tr^v_{i,j} = ti^v * W^v \forall v \in V \tag{3.17}$$

$$VC^v_{i,j} = BC * Pb^v * \frac{S_{i,j} * 1.852}{Vc^v} * SFCS_v \forall (i,j) \in A, v \in V \tag{3.18}$$

$$PC^v_j = BC * Pb^v * Tpmin^j * SFCP^v + xrate * GT^v * PD^v_j \forall j \in N, v \in V \tag{3.19}$$

$$CaC^v_{i,j} = SCD_v * CD_{i,j} * xrate \forall v \in V, (i,j) \in A \tag{3.20}$$

Equation 3.11 shows the objective function. It is split up into 2 main parts, costs dependant on total time spent, and costs dependent primarily on fuel usage and other costs accrued during sailing. These other costs are predominantly port costs and canal costs for the Kiel Canal. Fuel usage costs are due to sailing between nodes and time spent idle in port. Costs due to time are made up of operating costs and capital costs per hour. Equations 3.12 and 3.13 make sure that the flow between nodes is non-zero and deal with container flow constraints to and from a node. Equation 3.14 makes sure that the ships return to the origin by making sure that the trips to and from nodes are equal. Equation 3.15 makes sure that ship capacity is not exceeded by adding extra required trips to an arc. Equation 3.16 makes sure that the amount of ships chosen by the model does not exceed a designated amount. Equation 3.17 calculates the time required to fulfill all container flows by the chosen ship type. Equations 3.18, 3.19 and 3.20 are the voyage costs, port costs and canal costs respectively. Voyage costs are dependant on fuel consumption whilst at sea, port costs on fuel consumption in port and port dues to be paid to enter ports, and canal costs are dependant on a fixed cost per ship type per time the Kiel Canal is used. Note that distances are given in nautical miles, which are converted to kilometers by multiplying the nautical miles by 1.852. Furthermore, port costs and canal costs are found in euros. These are converted to dollars which makes them comparable with bunker costs.

4
Data acquisition

With the model completed, data is required for the case studies. Data is retrieved, to fill the parameters and sets in the mathematical model. This therefore includes the port, ship and canal parameters, container flows, time duration and costs.

4.1. Ports

The choice of ports is the first to be decided. By selecting a set of ports, container flows can be chosen, as well as the selection of the arcs between each port. The selection of ports taken into consideration for this thesis should be based on the current situation. Once a set of ports is created, a selection of major hubs, i.e. the origin ports, and feeder destinations are designated.

The method of finding suitable origin ports and destination ports is as follows. Firstly, a range of origin ports are looked for, that can service the region in question. It is important to know first where feeder ships can come from. Secondly, the current services from these origin ports into the region are found. These services identify the ports that are currently in use and the ships that are used to service them. It should be noted that it is not known if containers are unloaded at certain stops, only what the possible stops are. Looking at the feeder services from the origin ports shows the reach of them, and therefore which ports or areas can be taken out of the destination port set later. Thirdly, the container flows between origin and destination ports should be identified. Without a container demand from the origin port, a zero container destination port will be overlooked by the model.

It is chosen to look into the situation of the North Sea and Baltic Sea region. This region is at the tail end of the East-West trade lines originating in the Far East, and includes ports that service large areas of central and northern Europe, found in the range of ports from Le-Havre to Hamburg.

Using these origins, feeder services are looked for. A search for feeder services in the Northern-European region resulted in the following three companies: Samskip, Unifeeder and X-Press Feeders. All feeder services these companies provide can be seen in Appendix A. To make sure that no other feeder service is missed, feeder services found via CMA CGM and Maersk are added. A representative list from the ONE alliance was not included, because very little feeder routes were provided, and those were mostly services provided by one of the three feeder shipping companies mentioned above. All services found from the five shipping companies are shown in Appendix A. Note that duplicates may be found between service providers. This is due to either service providers using the same ship, or one service provider using multiple ships for their weekly services.

Feeder services included in Appendix A are those service ports that are in countries connected to the North Sea and Baltic Sea, including the Republic of Ireland. The first port in each list is the origin port, and each list ends with the final port. In most situations the first port is the same as the last one, or is situated nearby geographically. Most of the first ports are Bremerhaven, Hamburg or Rotterdam. Whereas routes beginning with one of the German ports tend to head North or East, whilst services starting in Rotterdam also include services to the British Isles. Most notable is that many of the services originating in Hamburg or Bremerhaven first stop at the other of the two ports, before heading out. On the return this can be seen too. Antwerp should also be mentioned as a major starting port. However, it seems that most of its routes are ei-

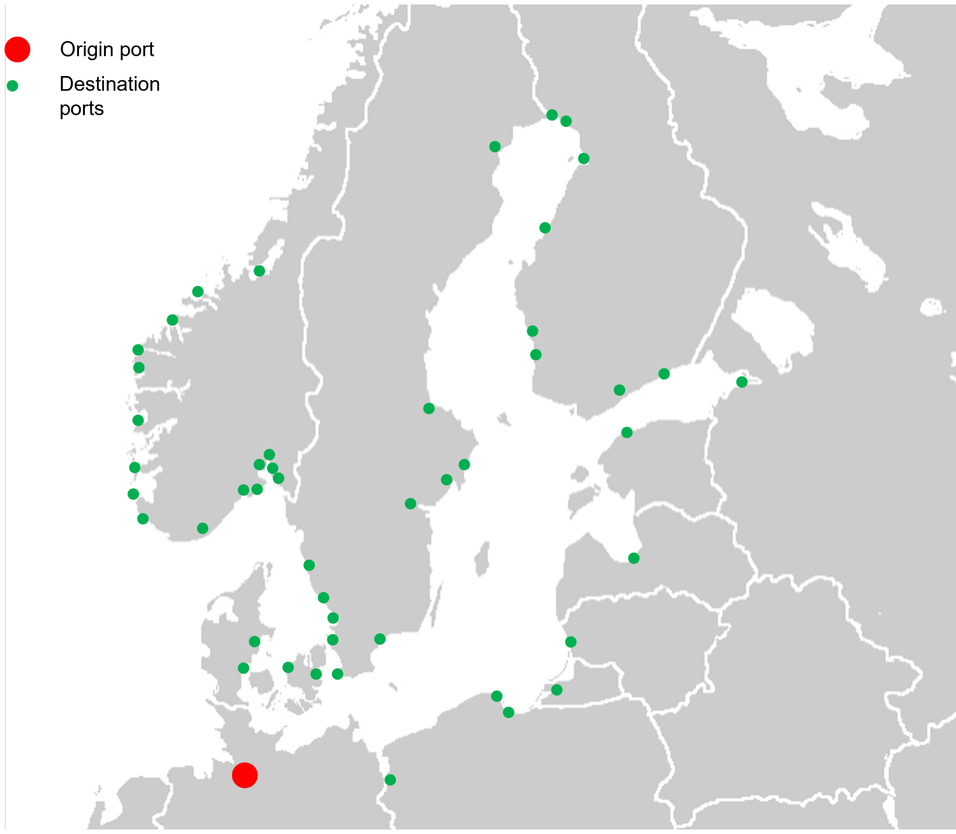


Figure 4.1: Locations of the origin and chosen feeder destinations [1]

ther to Ireland, or pass one of the other three on its way East. It is eventually decided to omit Rotterdam as an origin port, due to the complexity of the model. This means that feeder destinations in the United Kingdom are also omitted from the model.

With the choice of major hubs being Bremerhaven and Hamburg, destination ports can be determined. To ensure that chosen destination ports actually receive containers from the major hubs on a weekly basis, container flows will have to be determined in synchronisation with the choice of including certain destination ports.

The choice of destination ports is based on an analysis of the database of Eurostat, an open source database. Ports chosen are those classified as mainports by Eurostat, those which report information to the database [2] - [10]. A detailed version of the determination of destination ports via container flows is found in Appendix B. This results in 70 ports spread out across nine countries in the North Sea and Baltic Sea region. This list can be seen in table B.1. A map of all chosen port locations is seen in Figure 4.1.

4.1.1. Canal size restrictions

The Kiel Canal has size restrictions, which restrict the vessels able to traverse it. For lengths between 160 meters and 235 meters, and between 20 meters and 32.50 meters wide, maximum drafts range from 9.5 meters to 7 meters. Where the largest of lengths and widths, are only allowed to have a draft of 7 meters, and the smallest of lengths and widths 9.5 meters draft [8].

4.2. Container flows and arcs

For the container flows it is decided to take realistic values. It is important to take a base line of containers which mirrors the real world, to come to a final conclusion. The determination of container flows between origin and destinations is closely linked with the determination of those origin and destination ports. The determination of which is detailed in Section 4.1.

The assumption made for the container flows is that these flows not only include the containers which originated from outside Europe, but also those which originated in Europe. Be it that they were taken on-board during a stop on the way towards Bremerhaven or Hamburg, or that they are the result of trade between Germany and the country of the destination port. There is no way to make a distinction between the two. It is assumed that feeder ships operating between the origin and destinations, make no distinction between the containers originating from within Europe or outside of Europe.

Of the list of ports chosen in Section 4.1, the total container flow from North Sea German ports to these destinations is retrieved. The assumption is made that the German North Sea ports here are Bremerhaven and Hamburg. These ports were the origins of feeder routes from German North Sea ports in all cases found except for one. It should be noted that a number of these ports do not receive the same order of containers as the largest receivers do. Furthermore, due to limitations of the data retrieval, all ports situated in the Russian part of the Gulf of Finland are grouped together.

Container inflows from the German North Sea ports are retrieved from 2010 to 2020 from Eurostat [2–4, 6, 7, 10]. To give more weight to flows from later years, a weight scalar is added to each year, where the year of 2010 has the lowest weight scalar and 2020 the highest. This ensures that ports are still taken into account even if they had a year without a container inflow from German North Sea ports. The total of all of the scaled flows are then divided by the total number of the scalar values. This gives the weighted inflow of containers per year. These values are then divided by 52 to get the weighted inflow per week. If the value is less than 10 containers, the port is stricken from the list of ports.

The average container inflow is then calculated for the remaining ports. This is 636 TEU. Ports with a demand larger than this are denoted as large feeder port. These ports have a higher chance of a direct connection with a main hub than ports with smaller demands. This leaves a list of 47 ports remaining, of which 15 are large feeder ports. The final container inflows [TEU] for feeder ports from German North Sea ports are found in Table 4.1.

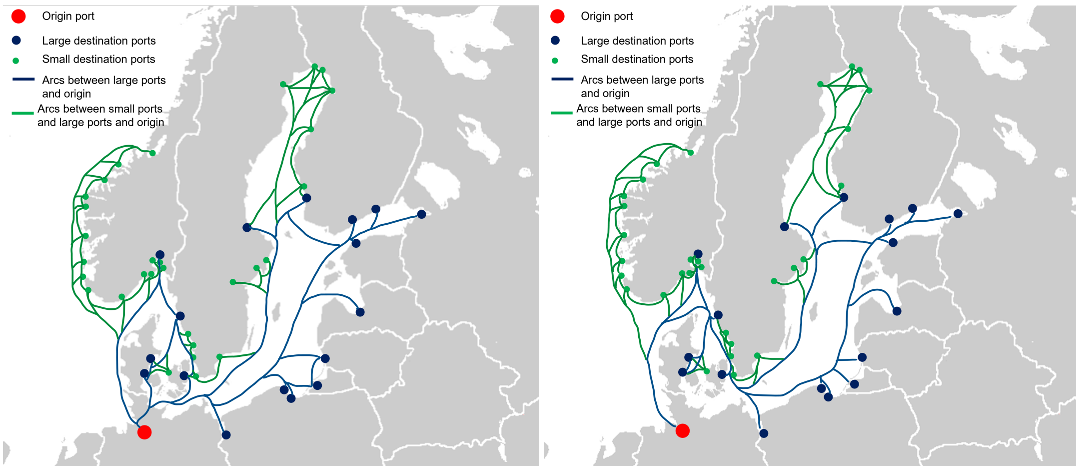
Once the location of the ports is known, arcs are placed between them and the origin port. Based on the spatial development of the port system shown by Notteboom [62], arcs are placed between the smaller feeder ports and their neighbours, and to the nearest larger feeder port. If the nearest large feeder port is not clear, arcs are drawn to multiple ports. The total list of arcs is seen in Tables B.2 - B.5 in Appendix B. The distances of the arcs are also included and are taken from sea-distances.org. Distances are checked by measuring the distance between the two nodes on Google Earth. Distances are in nautical miles. Figures 4.2a and 4.2b show a representation of the arcs placed between ports for small capacity ship types and large capacity ship types respectively.

4.3. Ships

This section presents the ship choice and parameters used in this thesis. Ships are chosen based on the capacities chosen by Mulder [57]. The container capacity of these ships starts at 200 TEU capacity and the largest of the feeders is 5000 TEU with various sizes in between. To help with further calculations it has been decided to assign a real world vessel to the capacities. The size parameters of the ships are valid and not chosen arbitrarily. In Table 4.2 the chosen capacities, capital and operating costs per week, and the real life comparisons can be seen.

Table 4.1: Container inflows per week from German North Sea ports to destination ports [2] - [10]

Feeder port	**Container inflow per week [TEU]**	**Feeder port**	**Container inflow per week [TEU]**
Åhus	48	Kristiansund	32
Ålesund	221	Larvik	139
Århus	1459	Malmö	46
Bergen	162	Måløy	108
Drammen	33	Moss	35
Egersund	38	Norrköping	401
Florø/Flora	20	Oslo	684
Fredericia	550	Oulu	145
Fredrikstad	218	Piteå	90
Gävle	445	Pori	103
Gdansk	2509	Porsgrunn	22
Gdynia	3150	Rauma	732
Göteborg	1364	Riga	1098
Halmstad	342	Russia (Gulf of Finland)	6513
HaminaKotka	1397	Russia (non Gulf of Finland)	1477
Haugesund	72	Södertälje	75
Helsingborg	305	Stavanger	78
Helsinki	1191	Stockholm	220
Kalundborg	44	Szczecin	404
Kemi	73	Tallinn	694
Klaipeda	935	Tornio	42
Københavns Havn	716	Trondheim	22
Kokkola	33	Varberg	13
Kristiansand	140		



(a) Arcs between origin and destination ports for small capacity ships (F1-F8)

(b) Arcs between origin and destination ports for large capacity ships (F9-F15)

Figure 4.2: Representation of arcs placed between the origin and feeder destinations [1]

Table 4.2: Vessel capacities, capital and operating costs, and real life comparison [33, 57]

Ship Name	**Ship Capacity** [TEU]	**Capital Cost** [k$/year]	**Operating Cost** [k$/year]	**Real Name**	**Real Ship Capacity** [TEU]
F1	200	800	1450	Iceland	200
F2	350	950	1525	Vanquish	365
F3	500	1100	1600	Pulau Hoki	500
F4	700	1400	1750	Regula	704
F5	800	1500	1800	X-press Mulhacen	809
F6	900	1600	1850	Formosa Container no. 4	900
F7	1000	1750	1925	Pegasus Peta	1000
F8	1250	2100	2100	Contship Ace	1267
F9	1500	2300	2200	Warnow Master	1496
F10	1750	2500	2300	Interasia Vision	1756
F11	2000	2700	2400	Aisopos II	2034
F12	2250	2950	2525	Seatrade blue	2256
F13	2500	3200	2650	Maersk Yorktown	2500
F14	4000	4500	3600	Zhong Wai Yun Bo Hai	4000
F15	5000	5400	4050	X-Press Guernsey	5001

Table 4.3: Size parameters of chosen ships [33]

Ship Name	**Lwl** [m]	**B** [m]	**T** [m]	**Dwt** [T]	**C_b**	**Vm** [m^3]	**Displacement**	**GT**
F1	79.5	16.8	4.1	2,375	0.695	3,806	3,901	2,089
F2	100	15.9	5	4,800	0.679	5,396	5,531	3,871
F3	121.1	20.8	6.2	9137	0.667	10,411	10,671	6,285
F4	132	19.2	7.7	8,524	0.67	13,068	13,394	7,170
F5	140	20.6	7.3	9,620	0.668	14,056	14,407	7,999
F6	139.7	23	8	11,975	0.663	17,041	17,467	9,280
F7	146	22.3	8.3	12,217	0.663	17,914	18,362	9,988
F8	159.8	23.3	8.5	13,715	0.66	20,888	21,410	14,016
F9	180.4	25	9.5	21,206	0.652	27,917	28,615	17,068
F10	170	28.1	9.5	23,500	0.650	29,518	30,256	19,800
F11	172	30	9.5	24,195	0.650	31,860	32,656	24,261
F12	185	30	9	22,380	0.652	32,572	33,387	24,905
F13	195	32.2	11	28,930	0.637	44,001	45,101	24,488
F14	210	37.3	13.3	54,000	0.626	65,176	66,806	44,426
F15	251	37.3	12.5	60,149	0.623	72,956	74,780	48,438

The determination of the block coefficient for each ship can be seen in Appendix B using size parameters shown in Table 4.3. Note that for the approximation of the propulsion power calculated by using the Holtrop and Mennen method, the $C_{b,wl}$ is used. The determination of the block coefficient in Appendix B is assumed to approximate the $C_{b,pp}$. Using the method of Holtrop and Mennen [40], the effective power required to sail at certain speeds is determined. From the effective power, various efficiencies of the power train are approximated, by using the Holtrop and Mennen method. The power diagonal shown in 'Design of Propulsion and Electric Power Generation Systems' by Klein Woud and Stapersma is used to approximate the brake horsepower of each ship for a certain sailing speed [44].

4.4. Costs

4.4.1. Operating costs and capital costs

A choice is made to use costs as the main factor when coming to a conclusion for this thesis. Costs are split up into three types, as is discussed in Section 3.2.3. Operating costs and capital costs for the chosen ship types have already been shown in Table 4.2. Capital costs and operating costs are taken from Mulder [57]. These costs will be divided up so that they are in *$ per hour*. This will make sure that for the duration of the deployment of a ship, the corresponding operating costs and capital costs are paid.

4.4.2. Voyage costs

The voyage costs are mostly made up by the fuel consumption. The fuel consumption is multiplied by the brake horsepower required to sail the chosen speed. In Section 4.3 the brake horsepower is calculated for each ship used. To calculate the fuel consumption whilst a ship is sailing, the specific fuel consumption (SFC) of that ship needs to be approximated. Figure B.1 shows the specific fuel consumption of prime movers [44]. For the ships chosen in this thesis, a SFC in the range of $170 < SFC < 190 g/kWh$ is used, depending on the specifications of the prime mover of the ships chosen. Further details for the approximation of the specific fuel consumption are seen in Appendix B.

The final part needed for the calculation of fuel consumption, is the time spent consuming. Time spent sailing depends on the distance of the arc between two ports and the speed at which the ship is travelling. It is assumed that each feeder ship sails at 15 kn, or 27.78 km/h. This speed is chosen as not all ships reach their maximum speed, but are sailing at reasonable speeds, so that transit time will not be too large. Table 4.4 shows the SFC and the brake horsepower of each ship approximately for operation at 15 kn. As long as the ship is in port, a different specific fuel consumption is used. The total fuel consumption is expected to be significantly less than when sailing. It is chosen to put the SFC for port time to be $50 g/kWh$ for each ship.

Table 4.4: Specific fuel consumption of chosen container ships and brake horsepower required to sail at 15 kn

Ship	**SFC** [g/kWh]	**Pb** [kW]
F1	190	2192
F2	190	2146
F3	190	2883
F4	190	2893
F5	190	3067
F6	170	3406
F7	170	3383
F8	190	3659
F9	190	4183
F10	170	4505
F11	170	4800
F12	170	4937
F13	170	5589
F14	170	6759
F15	170	7407

For the port costs, it is chosen to use data provided by the port authority of Riga. Riga is situated far from the major hubs, and is thought to be a suitable candidate for a baseline port tariffs. The tariffs are calculated from the moment ships enter its canal. Other costs levied by the port authority of Riga include berthing dues, sanitary dues, and unmooring and mooring costs. These costs are in order of mentioning: €0.042 per GT, €0.09 per GT, €0.062 per GT, and €0.17 per GT. In total port dues for a ship will be €0.364 per GT [35].

Canal costs are included for use of the Kiel Canal. Canal costs are made up of tariffs based on the GT of the ship, and extra costs for the use of external pilots which are obligatory for non-pleasure vessels. A table of the calculated costs is seen in table 4.5. The values of which are calculated from documents provided from the canal authority [24] and [25]. Note that where no costs are included, these ships are too large to traverse the canal and therefore will not be able to have costs applied to the ship type.

Table 4.5: Canal costs for the use of the Kiel Canal

Ship	**GT**	**Canal dues** [€]	**Pilot dues** [€]	**Total canal dues** [€]
F1	2089	638	896	1534
F2	3871	949	975	1924
F3	6285	1175	1068	2243
F4	7170	1231	1111	2342
F5	7999	1275	1146	2421
F6	9280	1350	1199	2549
F7	9988	1373	1218	2591
F8	14016	1582	1374	2956
F9	17068	-	-	-
F10	19800	-	-	-
F11	24261	-	-	-
F12	24905	-	-	-
F13	24488	-	-	-
F14	44426	-	-	-
F15	48438	-	-	-

4.5. Miscellaneous data

There are a number of data inputs thath do not fit with the other inputs. Firstly, time spent in port depends on the amount of containers being handled. However, this model does not include measures for port productivity, which means that a fixed time will be added to the total time spent for each time a ship enters a node, similarly to the benchmark suite created by Brouer et al. [22]. This will penalise ships that unload few containers and do not pick up containers. However, ships that unload large amounts of containers are expected to be assisted more by port authorities, which would increase the handling times. Brouer et al. uses 24 hours for berth time [23]. However, due to the nature of this feeder network, it has been chosen to set time spent in port to 12 hours per visit.

Secondly, various costs are acquired in euros. To be able to compare costs in dollars and euros, it has been chosen to convert costs in euros to dollars. The conversion rate of 1.159 is used to convert euros to dollars. This was the conversion rate on October 28 2021 according to x-rates.com.

5

Model Verification and Case Results

The model and all data needs to be verified. If not, then the results obtained from the model may be misleading. The model verification uses a smaller data set. Not all data used in this smaller data set equals the data presented in Chapter 4. This chapter is built up as follows: data used for the smaller model is presented, results of the smaller model is shown and the results of the hand calculation is also shown. Following the verification, a validation of the model is performed. Container flows and bunker costs of the same year ware put into the model. If the model shows that the ship types with the lowest total costs are similar to ship capacities of that year, the model is validated.

5.1. Model verification data and results

The data presented here, differs from data previously shown in Chapter 4. A smaller number of nodes and arcs are used to calculate a solution in a shorter time than for the full data set presented previously. This also makes the hand calculation much easier and less time consuming. If the results for the model and hand calculation for the smaller data set are the same, or similar, then the model is verified.

In total there are six nodes including the origin node, of which Hamburg is chosen. The other nodes are: Århus, Oslo, Haugesund, Ålesund and Trondheim. The nodes reflect a wider area container ports, of which their demand is added to the used nodes.

The inflow of containers for each flow is found in Table 5.1. A negative value means that there is an outflow of containers, and a positive value means that there is an inflow of containers. The arcs chosen for this model and the distances between the nodes are found in Table 5.2. The arcs between the nodes are seen in Figure 5.1. Only vessel F1 is used for the verification model.

Finally, the bunker costs chosen for the verification model are chosen so that low, medium and high costs are used. Results of the verification model are given for bunker costs of $200, $500, and $1000 per tonne. These are needed to calculate the fuel costs for sailing at sea and idle time spent in port. The expectation is that a decrease of the bunker cost will lead to a lower total cost. Similarly, raising the bunker cost will lead to a higher total cost.

Table 5.1: Inflow of containers for the verification model

Node	**Inflow**
Hamburg	-4967
Århus	2596
Oslo	1433
Haugesund	489
Ålesund	431
Trondheim	18

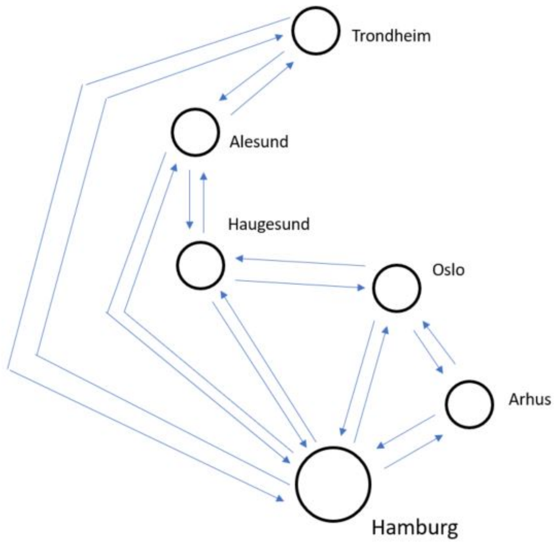


Figure 5.1: Arcs and nodes for the verification model

Table 5.2: Arcs between nodes and their distances for the verification model

Node i	**Node j**	**Distance** [NM]
Hamburg	Oslo	824
Hamburg	Haugesund	891
Hamburg	Ålesund	1156
Hamburg	Trondheim	1415
Århus	Oslo	482
Oslo	Haugesund	578
Haugesund	Ålesund	417
Ålesund	Trondheim	291
Århus	Hamburg	411
Oslo	Hamburg	824
Haugesund	Hamburg	891
Ålesund	Hamburg	1156
Trondheim	Hamburg	1415
Oslo	Århus	482
Haugesund	Oslo	578
Ålesund	Haugesund	417
Trondheim	Ålesund	291

For the results of the smaller data set, it is chosen to show multiple outcomes of the variables. This makes it easier to break down the calculations of the model and see what is calculated where. Results of the variables are shown in conjunction with the total cost. Seen in Tables 5.3, 5.4 and 5.5 are the arcs used, the amount of trips on those arcs and how many containers flow on the arcs. For the different bunker costs, the total time it takes to fulfil the container demand and the total costs of the system are calculated. These are seen in Tables C.1, C.2 and C.3. The time is calculated separately for the time spent on sea, and for time spent in port. The total time per arc is calculated and shown in Table 5.6 for each bunker cost.

Table 5.3: Verification results for bunker costs of $200 per tonne

Node i	**Node j**	**Trips**	**Container Flows** [TEU]
Hamburg	Århus	13	2596
Hamburg	Oslo	7	1371
Hamburg	Haugesund	2	400
Hamburg	Ålesund	3	600
Ålesund	Trondheim	1	18
Århus	Hamburg	13	0
Oslo	Hamburg	8	0
Haugesund	Hamburg	2	0
Ålesund	Hamburg	1	0
Trondheim	Hamburg	1	0
Haugesund	Oslo	1	62
Ålesund	Haugesund	1	151
Total Cost	$975625.15		
Total Time [h]	2898.333		

Table 5.4: Verification results for bunker costs of $500 per tonne

Node i	**Node j**	**Trips**	**Container Flows** [TEU]
Hamburg	Århus	13	2596
Hamburg	Oslo	8	1600
Hamburg	Haugesund	2	400
Hamburg	Ålesund	2	371
Oslo	Haugesund	1	167
Haugesund	Ålesund	1	78
Ålesund	Trondheim	1	18
Århus	Hamburg	13	0
Oslo	Hamburg	7	0
Haugesund	Hamburg	2	0
Ålesund	Hamburg	2	0
Trondheim	Hamburg	1	0
Total Cost	$1279201.81		
Total Time [h]	2898.333		

Table 5.5: Verification results for bunker costs of $1000 per tonne

Node i	**Node j**	**Trips**	**Container Flows** [TEU]
Hamburg	Århus	13	2596
Hamburg	Oslo	8	1600
Hamburg	Haugesund	2	400
Hamburg	Ålesund	2	371
Oslo	Haugesund	1	167
Haugesund	Ålesund	1	74
Ålesund	Trondheim	1	18
Århus	Hamburg	13	0
Oslo	Hamburg	7	0
Haugesund	Hamburg	2	0
Ålesund	Hamburg	2	0
Trondheim	Hamburg	1	0
Total Cost	$1785162.90		
Total Time [h]	2898.333		

Table 5.6: Calculated total time and total cost for various Bunker costs

BC [$ per tonne]	**Total time** [h]	**Total cost by hand** [$]	**Total cost model** [$]	**Difference to model** [%]
200	2898.33	975625.24	975625.15	0.00
500	2898.33	1279292.89	1279201.81	-0.01
1000	2898.33	1785163.98	1785162.90	0.00

From what is seen in Table 5.6, the results of the model are not exactly the same. However, looking at the percentage difference, the total costs calculated by hand are within acceptable limits to the total costs provided by the model.

5.2. Validation data and results

In this section, the model will be validated. To do this, the system with all nodes will be tested for container flows from 2020, as well as the bunker costs from that year. However, data for 2020 must be used with caution, because container flows and fuel costs may vary from previous years due to the Covid-19 pandemic. Once a container flow per week and a bunker cost is established, the total costs for using a single ship type is calculated. Without the total costs available for the whole region, a conclusion on the validity of the model will be based on the ships used by shipping companies in the region.

The container flows to each port are seen in Table 5.7. These flows differ from those used for the model in that these are taken from a singular year, whilst the container flows used in the case are weighted container flows. The bunker cost used for the validation will be the monthly average for 2020. Note that due to the Covid-19 pandemic, bunker costs may not be stable throughout the year and may be lower than the average cost for the years prior. Furthermore, to calculate the average cost of fuel in 2020, the costs for marine gas oil and very low sulfur fuel are used. As is seen in data retrieved from Clarksons [13]. Table 5.8 shows the bunker costs of marine gas oil and very low sulfur fuel oil from Rotterdam for 2020. The averages between them are around $350 per tonne. This bunker cost will be used for the validation.

Table 5.7: 2020 container flows from German North Sea ports to North Sea and Baltic Sea ports [10]

Ports	**Container demand 2020 per week** [TEU]	**Ports**	**Container demand 2020 per week** [TEU]
Åhus	0	Kristiansund	48
Ålesund	208	Larvik	211
Århus	1638	Malmö	0
Bergen	164	Måløy	140
Drammen	0	Moss	38
Egersund	51	Norrköping	408
Florø	9	Oslo	669
Fredericia	523	Oulu	107
Fredrikstad	150	Piteå	119
Gävle	50	Pori	0
Gdansk	2515	Porsgrunn	32
Gdynia	1664	Rauma	617
Göteborg	793	Riga	760
Halmstad	344	Russia (Gulf of Finland)	2790
HaminaKotka	678	Russia (non Gulf of Finland)	1594
Haugesund	119	Södertälje	79
Helsingborg	375	Stavanger	95
Helsinki	787	Stockholm	59
Kalundborg	34	Szczecin	353
Kemi	64	Tallinn	449
Klaipeda	420	Tornio	34
Københavns	653	Trondheim	27
Kokkola	33	Varberg	0
Kristiansand	120		

Table 5.8: Monthly MGO and VLSFO costs in Rotterdam 2020 [12, 13]

Month	**MGO Bunker Prices, Rotterdam** [$ per tonne]	**VLSFO Bunker Prices (0.5% Sulphur), Rotterdam** [$ per tonne]
January 2020	553.00	536.60
February 2020	481.19	451.69
March 2020	339.13	284.88
April 2020	263.88	210.69
May 2020	253.00	215.30
June 2020	331.13	284.38
July 2020	365.35	310.35
August 2020	367.75	318.44
September 2020	326.50	295.69
October 2020	327.40	309.25
November 2020	364.25	333.69
December 2020	412.75	369.94
Average 2020	365.44	326.74

Figure 5.2 shows the total costs for 2020 container flows and average bunker costs. From what is seen, the smallest ship is far the most expensive ship to use on its own. The total cost then comes down to the seventh ship type, then increases for the ninth ship type and then comes down again, but not to the same levels as the ships preceding the sudden rise. The sudden rise is due to the exclusion of the Kiel Canal, larger ships have to sail around the Northern tip of Denmark to get to the Baltic Sea. This increases distance and time, that has an effect on the fuel costs, capital costs, and operating costs respectively. Table 5.9 shows the total costs calculated, the best bound, and the cost per TEU per ship type in the system in orange, blue and grey respectively. The cost per TEU is read from the right side of the graph.

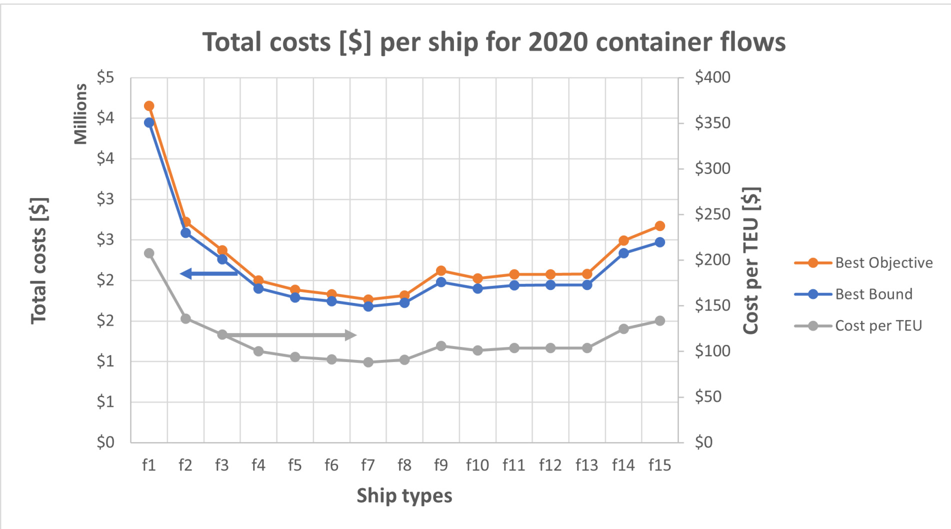


Figure 5.2: Total costs of 2020 container flows and bunker costs

Table 5.9: Total costs for 2020 container flows

Ships	Best objective	Best bound	Total cost per TEU
F1	$4 153 447.07	$3 946 785.51	$207.55
F2	$2 723 314.46	$2 587 945.43	$136.08
F3	$2 372 289.03	$2 259 955.71	$118.54
F4	$2 002 327.98	$1 902 216.75	$100.06
F5	$1 883 874.36	$1 789 706.78	$94.14
F6	$1 829 602.68	$1 742 546.74	$91.43
F7	$1 763 441.91	$1 677 031.80	$88.12
F8	$1 815 727.70	$1 725 039.39	$90.73
F9	$2 118 256.35	$1 980 854.95	$105.85
F10	$2 024 430.83	$1 899 079.37	$101.16
F11	$2 073 263.23	$1 938 719.26	$103.60
F12	$2 077 534.13	$1 942 622.67	$103.81
F13	$2 079 202.60	$1 944 477.25	$103.90
F14	$2 493 563.75	$2 336 764.73	$124.60
F15	$2 671 754.61	$2 471 403.41	$133.51

Table A.6 lists all ships in use between 25 May 2021 and 6 June 2021. Figure 5.3 shows the TEU capacity of the ships found. The average capacity of the ships is 1065 TEU, and the mean is 972 TEU. Comparing these to the ship types chosen for the model, they are in the range of the ship types F6, F7, and F8. The container capacities are: 900, 1000, and 1250 respectively. These ship types are those with the least total costs calculated by the model. Therefore it is concluded that the model is validated.

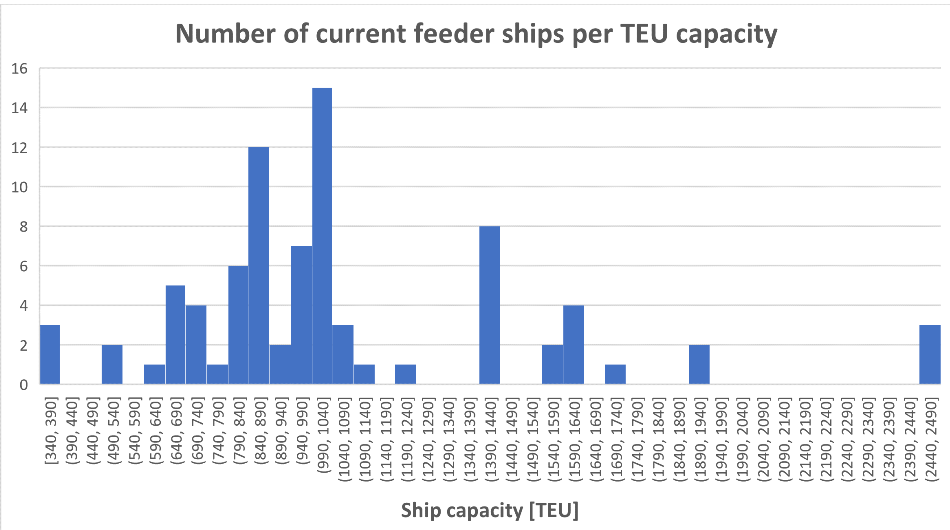


Figure 5.3: Container capacities of current feeder ships in the North and Baltic Seas [11, 14–17, 33]

6 Case studies

To come to a conclusion on the deployment of larger feeder container ships in the North Sea and Baltic Sea, it is chosen to vary three of the parameters used for the model. These parameters are the bunker costs, an increase flow of containers, and minimum of inflow to ports.

The expectation for the bunker costs is that for a higher bunker cost, a larger capacity ship will be more efficient and should lead to lower total cost per TEU. Similarly a lower bunker cost will allow smaller ships to be more competitive than larger ships in regards to cost per TEU. However, due to the nature of the model, where one type of ship is used to satisfy all demand in the region, a larger ship still have to fulfill the smallest of demands shown in the model. Furthermore, each time a ship stops for a small container inflow, it will lose the same amount of time in port, as it would for the largest of container inflows. From Clarksons it is seen that bunker prices for very low sulfur fuel oil and marine gas oil from Rotterdam, prices have fluctuated between $200 per tonne and around $1000 per tonne between 2010 and 2021, whereas of November 2021, prices are in the range of $500 and $600 per tonne [12, 13].

A rise in the flow of containers will mean that certain demands will be too large for the smallest container ships to remain efficient. With more containers in the system, the fuel cost efficiency of the larger container ships is increased. The choice has been made to double and triple the container flows from German North Sea ports to the feeder ports. A rise in container flows could be the consequence of multiple factors. Be it for an increase in purchase power, increase in population, or a redistribution from the main lines to the feeder services.

If ports are removed from the model, based on a minimum of TEU inflow, the assumption is made that smaller ship types have a higher total cost for the fulfillment of container flows in the region than larger ship types of the chosen ship types. Once the ports with a small inflow of containers are removed, the share of time spent at sea increases for all ships. This is more beneficial for larger container ships, as the economy of scale they provide is largely made whilst sailing between ports.

Calculations are completed with Gurobi Optimizer version 9.1.2 build v9.1.2rc0 (win64), a program that uses a branch and bound algorithm to optimise the solution. All experiments are completed with a Intel(R) Core(TM) i7-3630QM CPU @ 2.40GHz processor with 8.00 GB of RAM. All experiments are first left alone for solution to converge. If it is seen that the difference between the best objective and best bound, the experiment is restarted with a cut-off of the stagnant gap between the two. The gap between the two ranges is between 0% and 10%, where most of the gaps are around 5%.

6.1. Variation of bunker costs

The bunker costs are increased with steps of $100 per tonne, from $200 to $1000 per tonne. Graphs C.1 - C.9, show the total costs calculated by the model per step of increasing bunker costs. The three lines seen are: the best objective, the best bound, and the cost per TEU, all in $. The best objective is the total cost calculated by the model, the best bound is the best branch the model has got to in the branch and cut algorithm, and the cost per TEU is total cost divided by the total amount of containers in the system. For base line flows, there are 28,638 containers. All total costs for each step of bunker costs are seen in Figure 6.1.

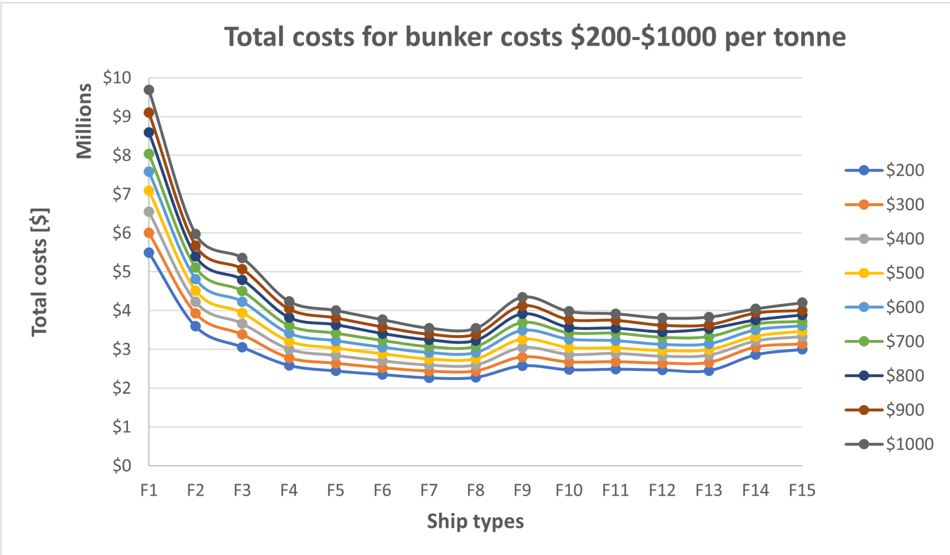


Figure 6.1: All total costs [$] for each bunker cost per ship type

There are three main developments from Figure 6.1. Firstly, the smallest ship (F1) is in all cases the ship type with the highest total costs. Secondly, the larger the ship capacity becomes, the lower the total costs are until ship type F9. Finally, after the sudden rise in costs for ship type F9, costs continue to fall until the final two ships where the costs rise. All total costs for each step of bunker costs are seen in Table C.4.

The smallest ships are efficient for the small flows, but are less efficient for ports with high inflows. In particular the ports, with a high inflow, and with a large distance between the origin port and themselves, make sure that the efficiency of the small ships drop considerably. Similarly, the largest ships will gain for the largest inflows and furthest distances, but will lose efficiency if they have to stop at the smallest ports constantly. This is exacerbated by a part of the region only having ports with small inflows and large distance between them. For the largest ship type (F15), one ship is expected to travel to all Norwegian ports, as well as most of the Danish and some Swedish ports in one trip. It would be more efficient to choose a smaller ship capacity and have two separate ships fulfill Norwegian container inflows, and Swedish and Danish container inflows. Finally, the sudden increase of the total costs for ship type F9 is due to the increase of distance between ports east of Skagen (DK), the most Northern tip of Denmark. The extra fuel cost incurred by sailing around the tip of Denmark is more than larger ships gain back by having a lower sailing time in total. However, this is not true for ship type F9, for which the time increases. The total time it takes to complete all demands for bunker cost of $200 to $1000 per tonne is found in Table 6.1. In fact, a change of bunker costs has little to no effect on the time spent fulfilling all container flows. The difference could be a consequence of the gap between best objective and best bound.

Table 6.1: Time to complete all container flows per ship and bunker cost from $200 to $1000 per tonne

Time [h]	**Bunker costs** [$ per tonne]								
Ships	200	300	400	500	600	700	800	900	1000
F1	15148	15139	15200	15285	15217	15135	15211	15183	15305
F2	8908	8990	9002	9009	9003	9022	9008	8968	8981
F3	6440	6520	6511	6510	6517	6504	6509	6495	6507
F4	4833	4796	4829	4821	4815	4815	4810	4827	4816
F5	4311	4315	4314	4307	4296	4309	4328	4312	4308
F6	3922	3924	3916	3926	3920	3920	3916	3911	3923
F7	3596	3613	3603	3596	3600	3599	3606	3597	3593
F8	3019	3026	3018	3018	3022	3026	3021	3022	3018
F9	3335	3353	3392	3378	3402	3389	3392	3395	3395
F10	2962	2992	2993	2985	3018	3009	2963	2990	3003
F11	2681	2693	2738	2708	2717	2741	2699	2723	2720
F12	2501	2514	2519	2507	2503	2521	2494	2508	2523
F13	2308	2362	2374	2339	2321	2343	2368	2317	2337
F14	1762	1800	1792	1781	1782	1795	1765	1781	1763
F15	1583	1579	1597	1596	1594	1583	1592	1582	1602

Transposing the axis so that the bunker costs are on the x-axis and the total costs of each ship is shown in the graph, it is seen that ship F8 has the lowest total costs for all bunker costs. Figure 6.2 shows this more prominently. Ship type F8 has a capacity of 1250 TEU and is the largest ship type which is allowed through the canal. Ship type F7 comes the closest to ship type F8. The total costs are seen in Table C.4. However, when the bunker costs increase, ship types F14 and F15 are more efficient than smallest ships in the set. Eventually the total costs for ship types F14 and F15 will have the lowest total costs. Though it is not known when this will happen as bunker costs larger than $1000 per tonne are not looked into. The reason being, is that costs have rarely risen higher than $1000 from what is seen in the relevant data [12, 13] .

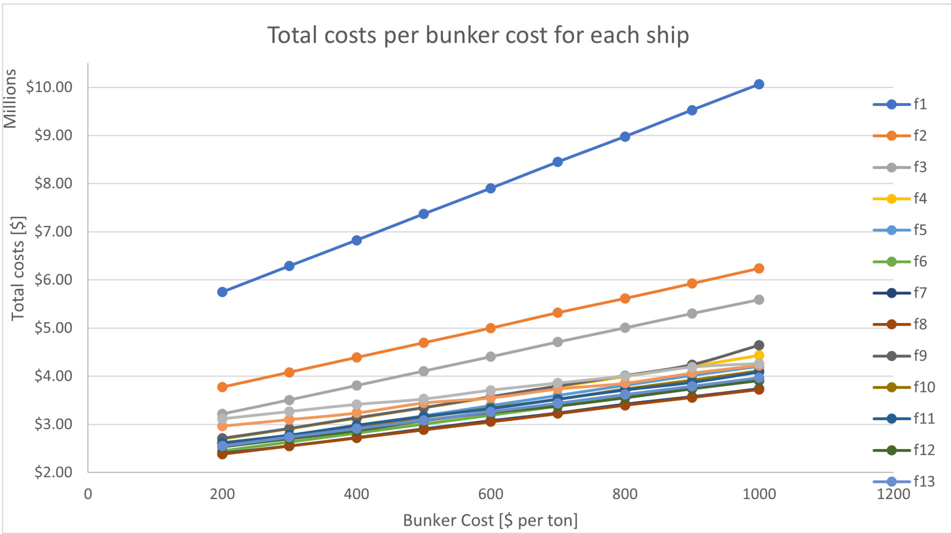


Figure 6.2: Total costs for each ship type per bunker cost

6.2. Increase of container inflow

The second case study uses an increase to the container inflows of destinations ports. This simulates an increase of demand due to an increase in population, buying power of the population, or both. The sum of the original inflows is in total 28,638 containers. For the second and third flows, there are 57,276 and 85,914 containers respectfully. The bunker cost chosen for the three container flows is $500 per tonne. The expectation is that for more containers in the system, the larger ships will be more efficient and will have lower total costs than the smaller ships. The graphs for the multiplication of container flows is found in Figures C.10, C.11 and C.12. Similarly as before, the total costs for all variations of container multiplications are shown in Figure 6.3, and total costs for ship types in Figure 6.4.

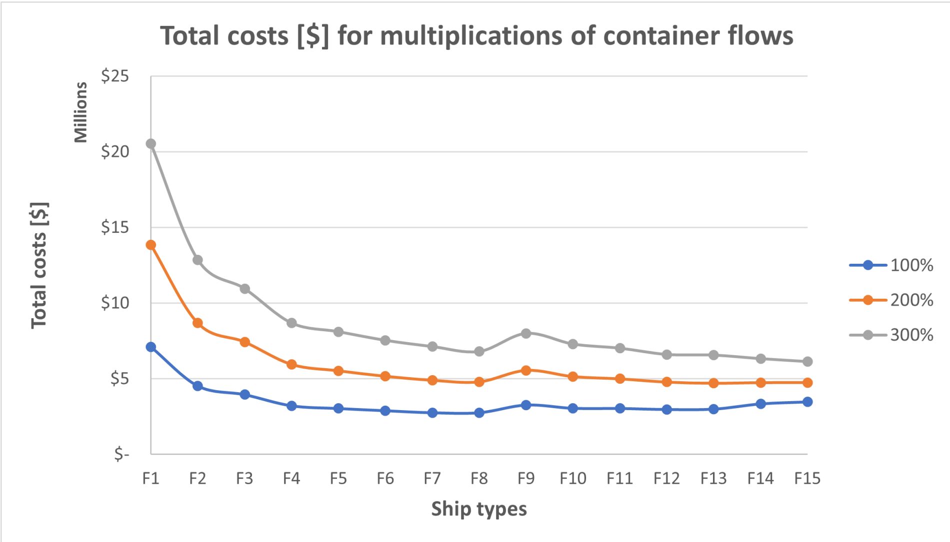


Figure 6.3: Total costs [$] for all multiplications of container flows

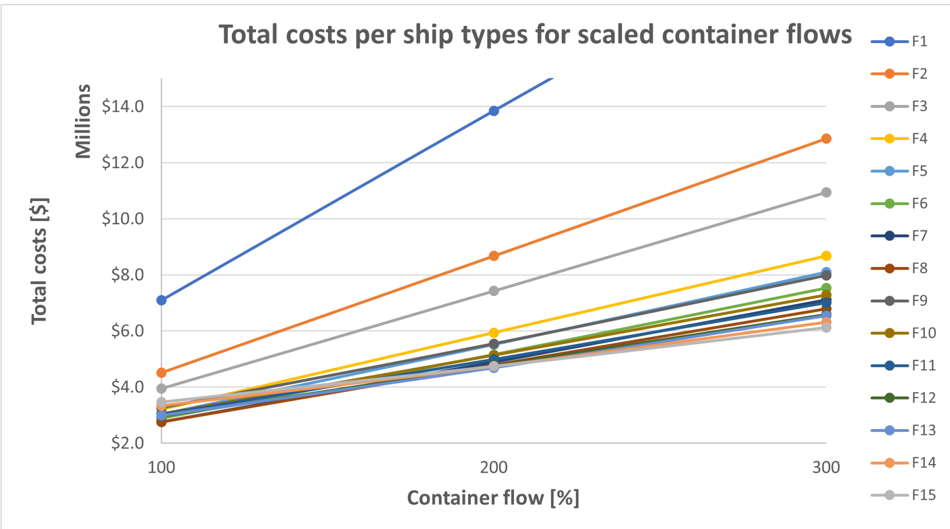


Figure 6.4: Total costs per ship types for scaled container flows

From what is seen in the graphs presented for an increase in container flows, is that differences between the ships are more pronounced the larger the increase is. Though the scales of the values have been changed, so that the former can be easily compared with Figures C.11 and C.12. The Kiel Canal has a larger effect on the total costs for the higher scalars. However, it seems that for a scalar of 2 the loss is quickly recovered by larger ship types. For a scalar of 3, the difference in increase of cost is more for the exclusion of the Kiel Canal than it is for the first two scalars. However, due to the amount of containers being moved within the system, the larger ship types become far more efficient than they would be previously.

The efficiency of the larger container ships can be seen in the cost per TEU. Table 6.2 shows the cost per TEU for each of the scalars of container flows. For each scalar, an increase of cost per TEU is seen for ship type F9 from ship type F8, as is seen in all other costs. However, for the increase in container flows, an increasingly larger ship is the turning point of a decrease in cost to an increase in cost. This means that when the total demand of containers increases in the region, it is to be expected that the capacity of container ships will increase. The gain of the larger capacity ship types is found in the capital and operating costs of the ship types. Table 6.3 shows the capital and operating cost per TEU for each ship type. Capital and operating costs reduce considerably for each step in ship type, where the largest capacity ship type sees the largest change. Table 6.4 shows the percentage of the costs per TEU for each ship type attributed to capital and operating costs. It is seen that for the smaller capacity ship types, the share of capital and operating costs remain the same for an increase of container flows. For the larger capacity ships, the share of the capital and operating costs are increasing noticeably. It can be concluded that the voyage costs for the larger capacity ships affect the total costs less than the capital costs and operating costs.

Table 6.2: Cost per TEU [$] per ship type for each increase of container flow

Ship types	100%	200%	300%
F1	246.54	241.43	240.23
F2	157.03	151.81	150.02
F3	137.42	130.07	127.95
F4	111.85	104.03	101.60
F5	106.28	97.22	94.87
F6	100.68	90.48	88.16
F7	97.20	86.27	83.36
F8	96.57	84.33	80.07
F9	111.91	97.01	92.87
F10	105.48	89.13	84.37
F11	105.96	86.82	80.90
F12	102.87	83.33	77.04
F13	103.14	82.29	75.90
F14	115.28	83.21	73.19
F15	117.97	82.50	70.57

Table 6.3: Capital and operating cost per TEU [$] per ship type for increase of all container flows

Ship types	100%	200%	300%
F1	137.46	133.80	132.17
F2	89.12	85.41	84.29
F3	70.26	66.07	64.92
F4	60.70	56.25	54.70
F5	56.81	51.82	50.69
F6	54.14	48.65	47.41
F7	52.82	47.19	45.85
F8	50.67	44.49	42.32
F9	60.76	52.86	51.08
F10	57.27	49.69	47.50
F11	55.20	47.06	44.57
F12	54.86	45.61	42.88
F13	54.69	44.54	42.03
F14	57.66	43.28	39.65
F15	60.28	43.60	38.96

Table 6.4: Percentage of cost per TEU for ship types due to capital costs and operating costs

Ship types	**100%**	**200%**	**300%**
F1	56%	55%	55%
F2	57%	56%	56%
F3	51%	51%	51%
F4	54%	54%	54%
F5	53%	53%	53%
F6	54%	54%	54%
F7	54%	55%	55%
F8	52%	53%	53%
F9	54%	54%	55%
F10	54%	56%	56%
F11	52%	54%	55%
F12	53%	55%	56%
F13	53%	54%	55%
F14	50%	52%	54%
F15	51%	53%	55%

6.3. Increase of minimum container inflow of ports

The final case study is to remove ports from the set, based on their container inflows. This will replicate a narrowing of choice of port for the ship types, and allow for pseudo berth size restrictions to be put in place. It can be seen that the ports with the highest inflows are those ports which are able to receive the largest ships chosen for this thesis. By only using the largest receivers of containers, will lead to an increase of the average container inflow of ports. For reducing the amount of destination ports in the model, it is chosen to increase the minimum inflow in steps of 200 until 1600 TEU. Once certain ports are taken out of the model, arcs connecting larger ports are broken. To make sure that certain ports are not isolated from the rest of the ports used in the region, new arcs are placed. This is done for each step of minimum inflow, so that the model has the choice of using these arcs for the low minimum inflows. For each step of minimum inflow, the amount of containers put into the system is also reduced. This is done to reduce the chance of problems arising during the calculations. The amount of containers in total flowing between the origin and the destination ports is seen in Table 6.5. The list of ports included for each step of minimal flow is seen in Table B.9. Figure 6.5 shows where ports are situated and when they are removed from the model.

Table 6.5: Number of containers [TEU] in the region per minimum inflow of destination ports

Minimal inflow [TEU]	**Number of containers** [TEU]
0	28638
200	27025
400	25719
600	23919
800	21093
1000	20158
1200	17869
1400	15108
1600	12172

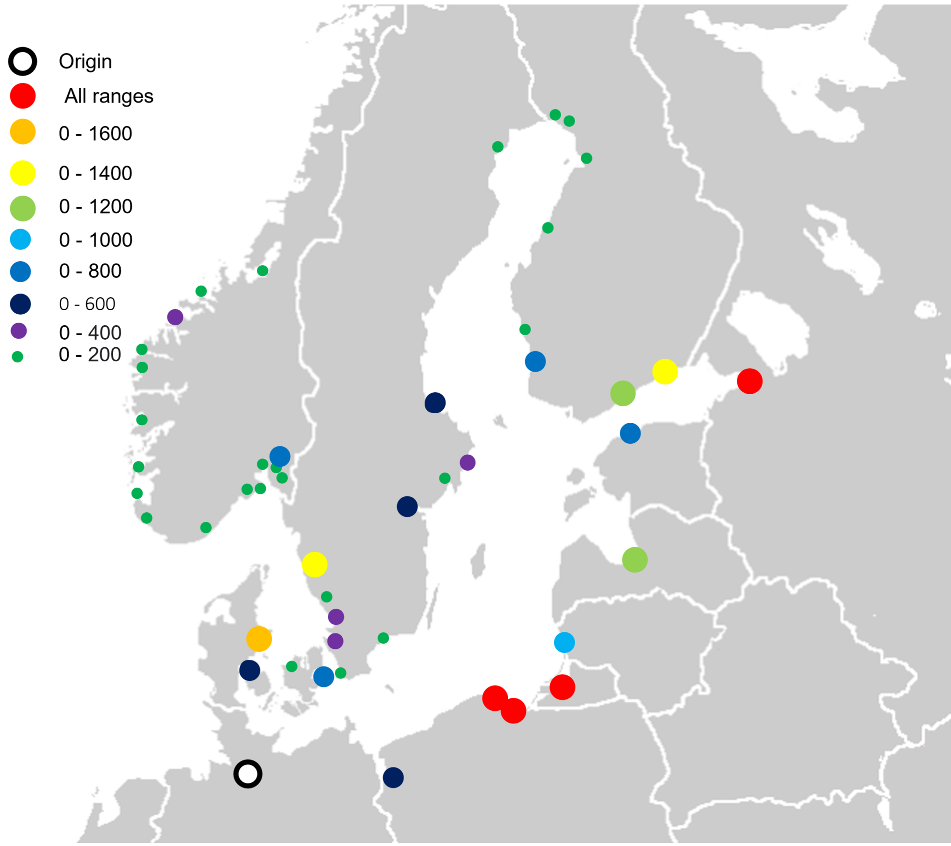


Figure 6.5: Locations of ports and ranges of TEU of ports which are included in the model, for increasing the minimum container inflow [1]

Figures C.13 - C.21 show the total costs per step of increase of minimal inflow to destination ports. Figure 6.6 shows the total costs of all ship types for the fulfillment of container flows between the origin and destination ports within the region for an increase of minimum inflows for destination ports. As is previously seen in Figure 6.2 and 6.3, total costs decrease for an increase in ship container capacity until ship type F9, and decreases further after ship type F9. However, on the contrary to the previous figures, larger ships have increasingly lower total costs than the ship types before F9 for higher minimum inflow to ports.

How ships perform in comparison to each other per minimal inflow step can be seen in Figure 6.7. From what is seen, is that for an increase of minimal container inflow of ports, the total costs of the larger ship types of become lower than the total costs of the ship type smaller than F9. For instance, ship types F14 and F15 are in the middle of the pack for when all ports are taken into consideration. However, once less ports are taken into account, F14 and F15 constantly have the lowest total costs compared to all other ships. Table 6.8 shows this more clearly. For the smallest of the chosen ship types, costs per TEU for each step per ship type are similar to each other for increasing minimal container inflow. A separation of costs per TEU per increase of minimum container inflow are only seen for larger ship types. Table C.5 shows the costs in detail per ship type and minimum inflow.

Removing ports from the model based on the container inflow has an effect on the choice of container ship type. Ship types with large capacities benefit from the removal of ports with a relative low container inflow. Whilst ship types which are small enough to traverse the Kiel Canal see little difference whether all ports are taken into consideration or only ports with a relative high inflow. The location of the ports and their container inflows is of importance here. Whereas most ports with an inflow smaller than 200 TEU per week are on the West coast of Norway or situated in the Gulf of Bothnia, all other ports bar 2 are situated on the Baltic Sea or around Denmark and the West coast of Sweden. This means that when the ports with the lowest container inflows are removed, the largest ship types used stand to gain the most in reduction of total costs. Each time the largest ship types enter the ports with the lowest inflows, the containers removed are a

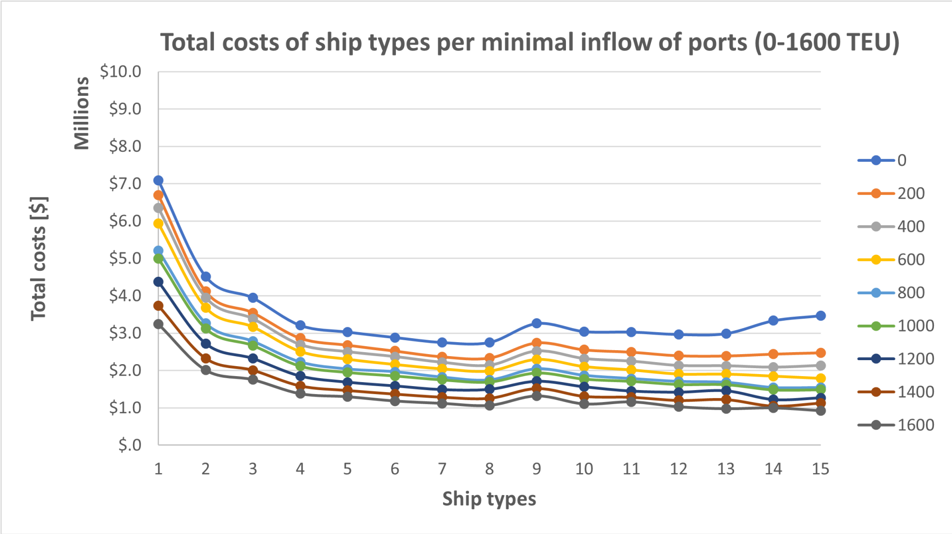


Figure 6.6: Total costs [$] for all ship types per minimal inflow of ports from 0 to 1600 TEU.

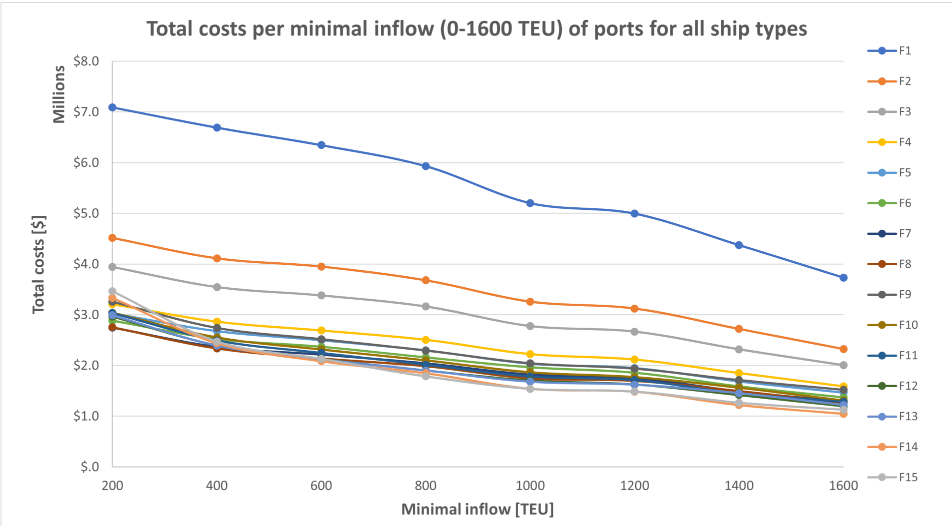


Figure 6.7: Total costs [$] of minimal inflow of containers [TEU] to ports per ship type.

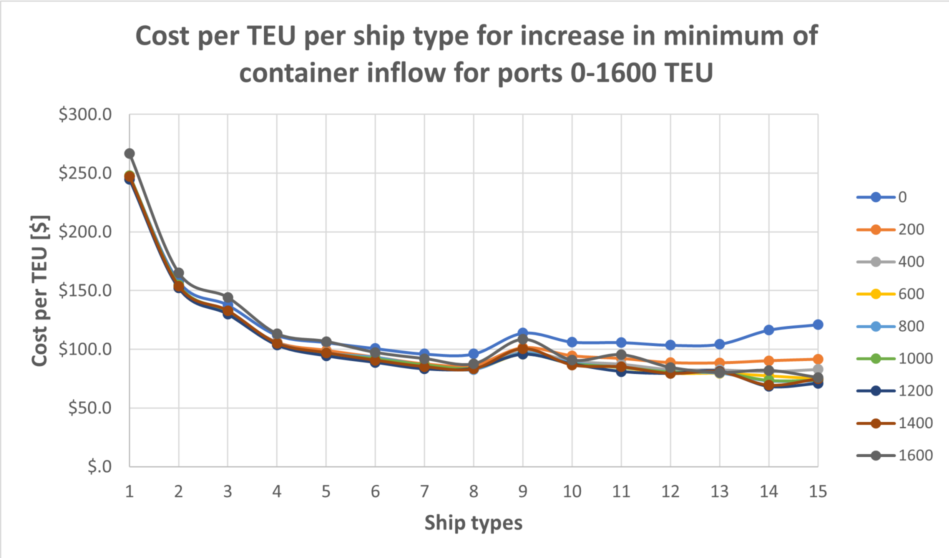


Figure 6.8: Cost per TEU for all ship types per minimal inflow of ports from 0 to 1600 TEU.

low percentage of their capacity. Whilst for the same port, a ship with a lower capacity has the same amount of containers removed which forms a higher percentage of its capacity compared to the larger capacity ship types. Furthermore, the fluctuation of cost per TEU is due to trips made by ship types not being optimal for their capacities. The utilisation rate of the ship types shows how much of the ship is filled with containers compared to the maximum container capacity of the ship type. Table 6.6 shows the utilisation rate of the ship types for trips leaving the origin port.

A utilisation rate of one means that the capacity of the ship multiplied by the trips made from the origin equals the total container inflow of all ports. A low rate means that there is container capacity on board which is unused. The lowest utilisation rates are for the ship types F14 and F15. This means that, depending on the total inflow of ports selected per increase of minimum container inflow, these ships are under performing in situations where the inflow of ports in the vicinity of each other is not easily divided by the capacity of these ships. However, they still may have the lowest cost per TEU of all the ship types per step increase of minimum container inflow.

Table 6.6: Utilisation rate of ship types leaving the origin port

	Minimum contianer inflow [TEU]								
Ship type	**0**	**200**	**400**	**600**	**800**	**1000**	**1200**	**1400**	**1600**
F1	0.9675	0.9721	0.9597	0.9645	0.9950	0.9979	0.9927	0.9939	0.9977
F2	0.9741	0.9652	0.9930	0.9904	0.9880	0.9930	0.9117	0.9810	0.9936
F3	0.9546	0.9652	0.9705	0.9763	0.9811	0.9833	0.9927	0.9747	0.9738
F4	0.9741	0.9416	0.9669	0.9763	0.9720	0.9930	0.9818	0.9810	0.9660
F5	0.9675	0.9130	0.9742	0.9645	0.9765	0.9691	0.9711	0.9939	0.9509
F6	0.9642	0.9384	0.9526	0.9843	0.9765	0.9738	0.9927	0.9875	0.9660
F7	0.9546	0.9319	0.9526	0.9568	0.9588	0.9599	0.9927	0.9443	0.9363
F8	0.9961	0.9400	0.9798	0.9568	0.9926	0.9486	0.9530	0.9297	0.9738
F9	0.9546	0.9008	0.9526	0.9380	0.9375	0.9599	0.9927	0.9156	0.9016
F10	0.9626	0.8579	0.9185	0.9763	0.9272	0.8861	0.9283	0.9592	0.9936
F11	0.9546	0.9008	0.9185	0.9966	0.9588	0.9163	0.8935	0.9443	0.8694
F12	0.9091	0.8579	0.9526	0.9664	0.9375	0.8959	0.9927	0.9592	0.9016
F13	0.9546	0.9008	0.9352	0.9568	0.9375	0.8959	0.8935	0.8633	0.9738
F14	0.8949	0.8445	0.9185	0.9966	0.7533	0.8399	0.8935	0.9443	0.7608
F15	0.9546	0.9008	0.8573	0.9568	0.8437	0.8063	0.8935	0.7554	0.8115

7
Conclusions and recommendations

This chapter discusses the results of the case studies and answers the main research question. The reasons behind the answer are also given. Following from the conclusions, recommendations are given for future research regarding feeder operations and the choice of container ship in Northern Europe.

7.1. Conclusions

The answer to the main question: 'What is the economical impact of larger capacity container ships for feeder operations between German North Sea ports and feeder destinations in Scandinavia and the Baltic States?' is twofold.

- If all ship types chosen in this thesis and all port inflows are taken into account, the current ships will most likely remain the main choice of feeder container ship in the region. These ships remain the first choice for a variation of the bunker cost. They remain competitive mainly due to the better fit of container flows from the German North Sea ports to the various sub regions in the North Sea and Baltic Sea. Once certain regions are no longer taken into account, the utilisation rate of ship types with lower container capacities does not weigh up against ship types with a higher container capacity due to the lower fuel economy of large capacity ships.
- As a consequence of smaller ports being removed from the model, the reduction in time spent by larger capacity ships outweighs the utilisation rates of the smallest capacity ships chosen for this thesis. This means larger capacity ships have a place for feeder operations in the North Sea and Baltic Sea region, as long as they service ports with considerable container inflows and do not sail to ports with low inflow in comparison.

The data provided by the outcome of the model and the choices of variables are based on the change in bunker price, an increase in container inflow of all ports and an increase in the minimum permitted inflow of containers to be taken into account in the model. Where for the bunker price, a range was chosen based on data from the past two decades, the change of container flows based on an increase of demand, and the removal of ports based on an increase of minimum inflow from the model. The increase of demand is thought to be a consequence of an increase of buying power, or an increase of population in the region.

From what is seen from the results of the model, the bunker prices have little to no effect on the choice. In all situations it seems that ship type F8 is the best choice, if only one ship type is used per experiment. Ship type F7 (1000 TEU) is close to ship type F8 (1250 TEU). In all cases, total costs rise rapidly for ship type F9 (1500 TEU) and come down again for larger ships until ship types F12 (2250 TEU) and F13 (2500 TEU), where a rise in costs is seen again. This fluctuation of total costs is thought to be a result of the size restrictions in the Kiel Canal. The extra distance the larger ships types have to sail offsets the economy of scale won for cost per TEU for the large capacity ships. For the highest bunker prices, the difference between ship types F12 - F13 and F15 is lower than for lower bunker prices. This means that if the bunker prices are increased further, it could be seen that ship type F15 may have lower total costs than F12 - F13, and eventually F8. However, due to the fact that bunker prices have rarely been above $1000 per tonne, it remains to be seen that the choice of container ship capacity will differ than currently.

An increase in container flows has a major impact on the choice of container ships. If ports have a larger inflow of containers, larger container ship types will perform better than their smaller counterparts regarding total cost. If the amount of containers is increased in the system, the time spent by ships will also be increased. Larger ships mostly gain their economy of scale compared to smaller ships at sea, where they are using less fuel per TEU than smaller ships [43]. For steps of 200% and 300% of the original container flows, larger ships will have lower total costs than the ships able to fit in the Kiel Canal. Ship type F15 (5000 TEU) has the lowest total cost for 300% of container inflows, and has one of the lowest total cost for 200% of the container inflows. The lowest for the latter seems to be ship type F13 (2500 TEU). However, due to variations in gap between the best objective found and best bound, chances are the difference between the two is negligible.

Decreasing the amount of ports in the system based on an increasing amount of minimum inflow of containers leads to a shift in which ship type has the lowest total cost. For a bunker cost of $500 per tonne and with no ports taken out, the largest ships able to traverse the Kiel Canal have the lowest total cost (F7 and F8). However, as soon as ports with low container inflows are removed, ship types with the largest container capacities will have the lowest total costs. Ship types F1 - F8 have a similar cost per TEU per step, regardless of the inflow to destination ports. However, ship types which are too large for the Kiel Canal see a reduction in their cost per TEU for an increase in minimum container inflow. Not all total costs are uniformly decreasing for the same minimal inflow. It is assumed that this is due to container flows having a worse fit for certain ship capacities. The largest factor here is thought to be the location of ports on the higher end of container inflows. These are in closer proximity to each other than to the ports on the lower end of the scale of container inflow. These are in particular on the West coast of Norway and the Gulf of Bothnia.

7.2. Recommendations

This section discuss what was thought about being added to the model, and what could be added in the future to give a clearer picture. There are multiple assumptions made prior to the creation of the model, which could be altered. These assumptions mainly concern transshipment, time spent by ship types, and port size restrictions.

For transshipment, there are three further options: allowing for transshipment with a cost and time penalty, allowing for transshipment without cost and time penalty, and allowing no transshipment between ship types. The third option is chosen for this thesis, and is done so by only allowing for one ship type per system optimisation. By doing this however, the choice of other ships that might fit some flows better cannot be made. One solution tried during this thesis was to allow transshipment and multiple ships during a system optimisation. The number of ships of a single ship type entering and leaving a port are made equal to each other. Two problems arose from this. Firstly, ships entering and leaving a port are not necessarily making connections to the origin and thus creating regions separately to other legs made by the ship type, so the need for transshipment is still there. Secondly, the final destination of the container may not be the final destination of the ship making the trip. This leaves the necessity for transshipment. The second problem is very similar to the first, but without the secondary route for the same ship type. A situation with no time and cost penalties would not mimic real world operations, as it takes time to put containers on to other ships, as well as there being an increase in costs. Nor is a solution with time and cost penalties created, due to not being able to distinguish containers for transshipment and not for transshipment. Possible ways to get around this problem is to set up routes and services, and then choose the most appropriate ship type. However, it was chosen to let the model do a simultaneous optimisation of the flows of containers and ships.

Time spent by ship types in the model is dependant on the time spent in port and time spent at sea. Time spent at sea is decided by the speed a ship is sailing at. For this thesis a set speed has been chosen. A set speed for all ships means that less input values are needed for fuel consumption. As a consequence, there are less variables in the model, which helps with calculation times. An increase of speed inputs, together with their required brake horsepower, will allow for ships to increase and decrease their speeds accordingly so to minimise total costs overall.

For each time a ship enters a port, a set amount is used to determine the time spent in port. This set amount is primarily used to emulate time required for unloading and loading containers. By using a set amount for each time a ship enters a node, regardless if containers are left behind or not, ships can be unnecessarily penalised for entering a node. This is mitigated by the amount of arcs created. A high amount of arcs allows for ships to sail more directly to where they need to be. However, the time calculated for being in a node does not fairly reflect the time required to unload or load containers. A solution looked into for this thesis attempted calculate the time required to unload containers based on the size of the ship and the port the ship was situated. The problem that arises from this solution is that there is no distinguishing between containers to be unloaded at a port, containers already there or yet to arrive, and containers entering a port on a ship but to be unloaded somewhere else.

Size restrictions are only partly implemented into the model. This is done for the Kiel Canal by using different distances between ports East of Denmark and the origin port. If all ship types are included, the distances between ports are also to be dependent on the ship type. This means that there are far more input values, compared to experiments for single ship types. Adding size restrictions for ports will ensure certain ship types will not enter ports too small for them. Size restrictions for ports can be modulated by using a binary value in the flow constraints per ship type for each port. Where are '1' allows a ship to use the port, and a '0' means that the flow into that port for a specific ship type will be zero too. The same binary value will also be for the first port of the arc. This ensures that the used ship type is allowed to enter the origin port in the first place. This solution is based on a solution provided by Álvarez which proposes to disable arc vessel-type combinations [20]. This approach would be used in the case of multiple ship types in one experiment, and therefore allow for ship types to set against each other.

A further possible addition to this thesis is to insert containers into the model before the hub. This means that the journey of the container will not start in a German North Sea port, but from its original origin port. By doing so, the model will be able to choose between leaving a container in a feeder hub and letting it make its way to its final destination by feeder ship, or to let it continue its journey on the same ship it started on from its original origin port. This means that ships with a capacity larger than 5000 TEU will have to be implemented into the model, and therefore more variables. This could increase the complexity of the model such that a more advance computer will be required to calculate an optimised result.

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A
Current routes and ships

Portcalls ->							
Antwerp	Hamburg	St. Petersburg	Antwerp				
Bremerhaven	Hamburg	norrkoping	Stockholm	Gävle	Hamburg	Bremerhaven	
Antwerp	Gothenburg	Antwerp					
Bremerhaven	Hamburg	Gothenburg	Aalborg	Kristiansand	Bremerhaven		
Bremerhaven	Hamburg	Drammen	Oslo	Fredikstad	Bremerhaven	Hamburg	
Bremerhaven	Hamburg	Fredericia	Århus	Helsingborg	Kalundborg	Bremerhaven	Hamburg
Bremerhaven	Hamburg	Ust-Luga	Kotka	Bremerhaven			
Bremerhaven	Hamburg	Helsinki	St. Petersburg	Hamburg			
Bremerhaven	Hamburg	Klaipeda	Gdansk	Gdynia	Bremerhaven	Hamburg	
Bremerhaven	Hamburg	Tallinn	Rauma	Bremerhaven	Hamburg		
Gdansk	Norrköping	Gävle	Gdansk				
Gdansk	Kotka	Gdansk					
Gdansk	Riga	Klaipeda	Gdansk				
Hamburg	Bremerhaven	Helsingborg	Copenhagen	Halmstad	Hamburg	Bremerhaven	
Hamburg	Kaliningrad	Klaipeda	Hamburg				
Hamburg	Fredericia	Århus	Gothenburg	Hamburg			
Hamburg	Bremerhaven	Moss	Oslo	Brevik	Larvik	Hamburg	Bremerhaven
Hamburg	Bremerhaven	Riga	Bremerhaven	Hamburg			
Hamburg	Bremerhaven	Copenhagen	Skagen	Hamburg	Bremerhaven		
Hamburg	St. Petersburg	Wilhelmshaven	Hamburg				
Hamburg	Szczecin	Gdynia	Hamburg				
Immingham	Rotterdam	Hamburg	Immingham				
Klaipeda	Gdynia	Oslo	Århus	Klaipeda	Gdynia		
London Gateway	Rotterdam	Teesport	Grangemouth	London Gateway	Rotterdam		
lubeck	Szczecin	Helsingborg	Halmstad	Oslo	Bremerhaven		
Rotterdam	Gothenburg	Århus	Hamburg	Rotterdam			
Rotterdam	Oslo	Brevik	Rotterdam				
Rotterdam	Vlissingen	Oslo	Helsingborg	Rotterdam	Vlissingen		
Rotterdam	Oslo	Brevik	frederikstad	Rotterdam			
Rotterdam	Moss	Drammen	Larvik	Kristiansand	Rotterdam		
Rotterdam	Kotka	Helsinki	Rotterdam				
Rotterdam	Vlissingen	Helsinki	Tallinn	St. Petersburg	Rotterdam	Vlissingen	
Rotterdam	Antwerp	St. Petersburg	Rotterdam	Antwerp			
Rotterdam	Antwerp	Riga	Klaipeda	Rotterdam	Antwerp		
Rotterdam	Immingham	Grangemouth	Rotterdam				
Rotterdam	Felixstowe	Teesport	Rotterdam				
Rotterdam	Felixstowe	Grangemouth	Rotterdam	Felixstowe			
Rotterdam	Felixstowe	Southshields	Rotterdam				

Table A.1: Northern European Feeder services by Unifeeder [17]

Portcalls ->							
Bremerhaven	Hamburg	Tallinn	Rauma	Bremerhaven	Hamburg		
Hamburg	Ålesund	Holla	Tananger	Sauda	Kvinesdal	Hamburg	
Hamburg	St. Petersburg	Hamburg					
Hamburg	Bremerhaven	Riga	Bremerhaven	Hamburg			
Hamburg	Bremerhaven	Klaipeda	Gdansk	Gdynia	Bremerhaven	Hamburg	
Rotterdam	Helsinki	Kotka	Rotterdam				
Rotterdam	Tananger	Haugesund	Bergen	Tananger	Amsterdam	Rotterdam	
Rotterdam	Ålesund	Rotterdam					
Rotterdam	Tananger	Bergen	Ålesund	Trondheim	Bjugn	Bodo	->
->	Harstad	Tromso	Melkoya	Alta	Tromso	Senjahopen	->
->	Sortland	Ålesund Frigocare	Tananger	Velsen	Rotterdam		
Rotterdam	Tananger	Bergen	Ålesund	Trondheim	Harstad	Tromso	>
->	Sortland	Steinshamn	Ålesund	Lutelandet	Tananger	Velsen	Rotterdam
Rotterdam	Oslo	Brevik	Fredrikstad	Rotterdam			
Rotterdam	Oslo	Brevik	Rotterdam				
Rotterdam	Moss	Drammen	Larvik	Kristiansand	Rotterdam		
Rotterdam	St. Petersburg	Rotterdam					
Rotterdam	Hamburg	St. Petersburg	Rotterdam				

Table A.2: Northern European Feeder services by Samskip [16]

portcalls ->									
Antwerp	Rotterdam	Riga	Klaipeda	Antwerp					
Antwerp	Rotterdam	St. Petersburg	Antwerp						
Hamburg	Fredericia	Copenhagen	Helsingborg	Bremerhaven	Hamburg				
Hamburg	Bremerhaven	Klaipeda	Hamburg						
Bremerhaven	Hamburg	Gdynia	Gdansk	Bremerhaven					
Bremerhaven	Hamburg	Kaliningrad	Århus						
Antwerp	Zeebrugge	Kokkola	Kemi	Oulu	Zeebrugge				
Rotterdam	Gothenburg	Rotterdam							
Hamburg	Bremerhaven	Sodertalje	Pitea	Tornio	Kemi	Oulu	Kokkola	Sodertalje	Hamburg

Table A.3: Northern European Feeder services by x-Press Feeders [11]

Portcalls ->									
Bremerhaven	Egersund	stavanger	Haugesund	fusa	Bergen	floro	maaloey	aÅlesund	Bremerhaven
Bremerhaven	Helsinki	Rauma	Bremerhaven						
Bremerhaven	Bremerhaven	Hamburg	Kristiansand	Bremerhaven	Bremerhaven				
Bremerhaven	Fredericia	Bremerhaven							
Bremerhaven	Hamburg	Szczecin	Bremerhaven						
Bremerhaven	Bremerhaven	Riga							
Bremerhaven	Bremerhaven	Helsingborg	Halmstad	Bremerhaven	Bremerhaven				
Gdansk	Tallinn	Klaipeda	Gdansk						
Hamburg	Bremerhaven	Oulu	Raahe	Tornio	Hamburg				
Hamburg	Bremerhaven	Bremerhaven	Oulu	Kemi	Hamburg	Bremerhaven	Bremerhaven		
Hamburg	Drammen	Fredrikstad	Oslo						
Hamburg	Bremerhaven	Bremerhaven	Moss	Oslo	Brevik	Larvik			
Hamburg	Bremerhaven	Bremerhaven	kalundborg	Hamburg	Bremerhaven	Bremerhaven			
Hamburg	kalundborg	Århus	Gothenburg	Hamburg					
Hamburg	Hamburg	Bremerhaven	Kaliningrad						
Helsingborg	Bremerhaven	Bremerhaven	Hamburg						
Rotterdam	Rotterdam	Gothenburg	Rotterdam	Rotterdam					
Rotterdam	Cork	Brest	Rotterdam						
Rotterdam	Belfast	Dublin	Rotterdam						
Rotterdam	Dublin	Belfast	Rotterdam						
Rotterdam	Felixstowe	Southshields	Grangemouth	Antwerp	Rotterdam				
Rotterdam	Grangemouth	Southshields	Felixstowe	Rotterdam					
Rotterdam	Cork	Rotterdam							
Rotterdam	Cork	Rotterdam							
Wilhelmshaven	Bremerhaven	Gdansk	Tallinn	Gävle	Norrköping	Wilhelmshaven	Bremerhaven		

Table A.4: Northern European Feeder services by Maersk [15]

portcalls ->										
Antwerp	Hamburg	Bronka	St. Petersburg	Antwerp						
Antwerp	Dublin	Cork	Antwerp							
Antwerp	Rotterdam	Dublin	Antwerp							
Antwerp	Zeebrugge	Dublin	Antwerp							
Bremerhaven	Hamburg	Kaliningrad	Århus	Bremerhaven						
Bremerhaven	Hamburg	Helsingborg	Fredericia	Bremerhaven						
Bremerhaven	Hamburg	Drammen	Oslo	Fredrikstad	Bremerhaven					
Bremerhaven	Hamburg	Norrköping	Stockholm	Gävle	Hamburg	Bremerhaven	Riga	Bremerhaven		
Bremerhaven	Szczecin	Helsingborg	Halmstad	Oslo	Bremerhaven					
Bremerhaven	Hamburg	Klaipeda	Gdynia	Bremerhaven	Hamburg	Helsinki	Bremerhaven			
Bremerhaven	Hamburg	Gothenburg	Aalborg	Kristiansand	Bremerhaven					
Gdansk	Norrköping	Gävle	Gdansk							
Gdansk	Kaliningrad	Kotka	Gdansk							
Hamburg	Bremerhaven	Pitea	Tornio	Kemi	Oulu	Sodertälje	Hamburg			
Hamburg	Fredericia	Århus	Gothenburg	Hamburg						
Hamburg	Bremerhaven	kalundborg	Copenhagen	Hamburg						
Hamburg	Rotterdam	Riga	Klaipeda	Rotterdam	Gdansk	Rotterdam	Helsinki	Kotka	Hamburg	
Hamburg	Bremerhaven	Moss	Oslo	Brevik	Larvik	Hamburg				
Hamburg	Szczecin	Hamburg								
Hamburg	Kaliningrad	Klaipeda	Hamburg	Gdynia	Hamburg					
Hamburg	Bremerhaven	Hamburg	Stavanger	Haugesund	Bergen	Floro	Orkanger	Ålesund	Ikornnes	Hamburg
Hamburg	Helsingborg	Halmstad	Gothenburg	Hamburg						
Hamburg	Ust-Luga	Kotka	Bremerhaven	Hamburg	Bremerhaven					
Hamburg	Bremerhaven	Helsingborg	Copenhagen	Halmstad	Hamburg					
Hamburg	Rotterdam	Gothenburg	Århus	Hamburg						
London Gateway	Rotterdam	Teesport	Grangemouth	London Gateway						
Rotterdam	Helsinki	Rotterdam								
Rotterdam	Moss	Drammen	Larvik	Kristiansand	Rotterdam					
Rotterdam	Floro	Ålesund	Orkanger	Mo I Rana	Straumen	Orkanger	Ålesund	Rotterdam		
Rotterdam	Stavanger	Haugesund	Svelgen	Rotterdam						
Rotterdam	Oslo	Brevik	Rotterdam							
Rotterdam	Oslo	Brevik	Fredrikstad	Rotterdam						
Rotterdam	Bronka	St. Petersburg	Rotterdam							
Rotterdam	Dublin	Rotterdam								
Rotterdam	Liverpool	Rotterdam	Cork	Rotterdam	Dublin	Rotterdam				
Rotterdam	Felixstowe	Grangemouth	Rotterdam							
Rotterdam	Felixstowe	Southshields	Rotterdam	Immingham	Teesport	Grangemouth	Antwerp	Rotterdam		
Rotterdam	Southampton	Dublin	Cork	southampton	Rotterdam	Liverpool	Belfast	Greenock	->	
->	Southampton	Rotterdam	Dublin	Rotterdam						
Vlissingen	Rotterdam	Oslo	Helsingborg	Vlissingen						
Wilhelmshaven	Hamburg	Bronka	St. Petersburg	Wilhelmshaven						

Table A.5: Northern European Feeder services by CMA CGM [14]

Name	Operator	Type	Geared	Nominal Capacity	Reefer Plugs	Dwt	Built	Flag	Speed
A LA MARINE	CMA - CGM	CC	N	1 440	316	20 073	2009	BELGIUM	19
ALDEBARAN J	BG FREIGHT LINES BV	CC	N	962	170	10 977	2006	ANTIGUA AND BARBUDA	18
ANDREA	UNIFEEDER A S	CC	N	868	234	11 200	2005	GIBRALTAR	18
ANGELA	SEA CONSORTIUM	CC	N	868	234	11 150	2005	GIBRALTAR	18
ANINA	OOCL	CC	N	868	234	13720	2006	MADEIRA	18
ARA Amsterdam		CC	N	1025	249	13425	2010	MADEIRA	18
ARIES J	CMA - CGM	CC	N	1 036	250	13 200	2011	CYPRUS	19
ATLANTIC COAST	SEA CONNECT UAB	CC	N	660	100	7850	1996	CYPRUS	18
AURORA	SEA CONSORTIUM	CC	N	868	150	11 380	2001	ANTIGUA AND BARBUDA	18
AVA D	UNIFEEDER A S	CC	N	1 572	155	20 600	2007	LIBERIA	19
BALTIC FULMAR	X-PRESS FEEDERS	CC	N	1600	314	16000	2005	CYPRUS	20
BALTIC PETREL (SCA TUNADAL)	SCA TRANSFOREST AB	CC	N	1600	314	16000	2005	CYPRUS	20
BALTIC SHEARWATER (SCA MUNKSUND)	SCA TRANSFOREST AB	CC	N	1600	314	16000	2005	CYPRUS	20
BALTIC TERN	X-PRESS FEEDERS	CC	N	1638	311	15956	2005	CYPRUS	20
BEATE	UNITED FEEDER SERVICE LTD	CC	N	868	234	11 150	2005	GERMANY	18
BERNHARD SCHEPERS	UNITED FEEDER SERVICE LTD	CC	N	1 036	250	13 030	2011	ANTIGUA AND BARBUDA	19
BG IRELAND	BG FREIGHT LINES BV	CC	N	962	170	11 178	2007	CYPRUS	18
BIANCA RAMBOW	UNIFEEDER A S	CC	N	868	150	11 286	2004	GERMANY	19
BUXTEHUDE	REEDEREI RAMBOW	CC	N	613	468	11200	2006	ANTIGUA	18
CALISTO	UNIFEEDER A S	CC	N	1 578	250	19 550	2005	LIBERIA	20
CHARLOTTA B	UNIFEEDER A S	CC	N	1 421	300	17 861	2009	LIBERIA	19
CHRISTOPHER	UNIFEEDER A S	CC	N	1 440	316	19 800	2008	ANTIGUA AND BARBUDA	20
CMA CGM LOUGA	CMA - CGM	CC	N	2 487	747	34 693	2018	MALTA	20
CMA CGM NEVA	CMA - CGM	CC	N	2 487	747	34 694	2018	MALTA	20
CMA CGM PREGOLIA	CMA - CGM	CC	N	2 487	747	34 693	2018	MALTA	20
CONMAR GULF	UNIFEEDER A S	CC	N	698	120	8 300	2007	PORTUGAL	17
CT Rotterdam	EUCON	CC	N	962	170	11 020	2009	CYPRUS	18
DELPHIS BOTHNIA	DIAMOND LINE	CC	N	1500	494	24427	2016	HONG KONG	18.5
DELPHIS Gdansk	DIAMOND LINE	CC	N	1500	494	24427	2017	HONG KONG	18.5
DORNBUSCH	MANN LINES LTD	CC	N	508	50	5210	1996	GERMANY	15.5
ELBFEEDER	EUCON	CC	Y	974	170	11 050	2008	CYPRUS	18
ELBSAILOR	UNIFEEDER A S	CC	N	1 084	250	14 230	2012	ANTIGUA AND BARBUDA	17
ELBSKY	UNIFEEDER	CC	N	1025	245	13425	2011	ANTIGUA	18
ELBSTAR	UNITED FEEDER SERVICE LTD	CC	N	877	231	12 306	2009	ANTIGUA AND BARBUDA	18
ELBSUMMER	UNITED FEEDER SERVICE LTD	CC	N	1 025	249	14 800	2009	ANTIGUA AND BARBUDA	18
ELBTRADER	EUCON	CC	N	962	170	11 200	2008	CYPRUS	18
EMILIA	X PRESS FEEDERS PANAMA SA	CC	N	700	144	7 114	1999	ANTIGUA AND BARBUDA	17
ENERGIZER	UNITED FEEDER SERVICE LTD	CC	N	750	190	9 285	2004	NETHERLANDS	18
ESPERANCE	UNIFEEDER A S	CC	N	1 436	431	22 600	2011	NETHERLANDS	19
ESPOIR	UNIFEEDER A S	CC	N	1 436	431	22 600	2011	NETHERLANDS	19
FIONIA SEA	DFDS	RR				11235	2009	UK	20
GRETE SIBUM	UNITED FEEDER SERVICE LTD	CC	N	1 036	250	12 952	2008	CYPRUS	18.5
HANNI	UNIFEEDER A S	CC	N	658	102	6 850	1998	GERMANY	17
HEINRICH EHLER	UNIFEEDER A S	CC	N	1 425	300	17 861	2008	PORTUGAL	14
HEINRICH SCHEPERS	CONTAINERSHIPS - CMA CGM GMBH	CC	N	1 036	250	13 031	2012	PORTUGAL	19
HELGA	X PRESS FEEDERS PANAMA SA	CC	N	822	150	8 700	2003	NETHERLANDS	19

HELMUT	SEA CONSORTIUM	CC	N	868	234	11 390	2006	PORTUGAL	18
IDA RAMBOW	UNIFEEDER A S	CC	N	1 008	238	13 740	2007	GERMANY	18
ITALIAN EXPRESS	UNIFEEDER	CC	N	1082	250	14150	2012	GIBRATAR	19
JORK	COSCO SHIPPING LINES CO LTD	CC	N	868	150	11 200	2001	CYPRUS	18
JSP SKIRNER	UNIFEEDER A S	CC	Y	966	252	11 500	2006	ANTIGUA AND BARBUDA	19
JSP SLIDUR	SEA CONSORTIUM	CC	N	868	234		2007	CYPRUS	18
JUTLANDIA SEA	DFDS	RR				11553	2010	UK	20
KATHARINA SCHEPERS	UNIFEEDER A S	CC	N	1 036	250	13 030	2012	CYPRUS	15
KRISTIN SCHEPERS	UNIFEEDER A S	CC	N	803	180	9 300	2008	CYPRUS	18
MAIKE D	UNIFEEDER A S	CC	N	660	150	7 946	2000	LIBERIA	18
MEANDI	UNIFEEDER A S	CC	N	803	180	9 300	2006	PORTUGAL	18
MITO	UNITED FEEDER SERVICE LTD	CC	N	1 118	220	13 760	2006	PORTUGAL	20
MOTIVATION D	SEA CONSORTIUM	CC	N	917	200	10 600	2006	LIBERIA	18
MUNKSUND	UNIFEEDER A S	CC	N	1 025	249		2012	MALTA	18
NCL Ålesund	NCL NORTH SEA CONTAINER LINE AS	CC	Y	862	234	11 200	2006	ANTIGUA AND BARBUDA	18
NCL AVEROY	NCL NORTH SEA CONTAINER LINE AS	CC	Y	862	234	11 190	2006	PORTUGAL	18
NCL SVELGEN	NCL NORTH SEA CONTAINER LINE AS	CC	Y	862	234	11 416	2005	PORTUGAL	18
NJORD	UNIFEEDER A S	CC	N	801	150	9 593	2007	NETHERLANDS	18
NORDICA	X-PRESS FEEDERS	CC	N	1036	250	13031	2011	NETHERLANDS	18.5
ORION		CC	Y	698	120	8214	2008	ANTIGUA	17.3
PACUL	UNITED FEEDER SERVICE LTD	CC	N	1 134	232	12 545	2002	MARSHALL ISLANDS	19
PANTONIO	UNITED FEEDER SERVICE LTD	CC	N	698	120	8 021	2007	CYPRUS	17
PERSEUS	BUSS SHIPPING	CC	N	774	498	13425	2010	ANTIGUA	18
PIRITA	SEA CONNECT UAB	CC	N	660	100	7946	1995	MADEIRA	18.6
RIJNBORG	UNIFEEDER A S	CC	N	1 700	200	15 830	2007	NETHERLANDS	20
RUMBA	NCL NORTH SEA CONTAINER LINE AS	CC	N	657	116	8 015	2003	GIBRALTAR	18
SAMSKIP CHALLENGER	WILSON ASA	MP	Y	384		4766	1995	BARBADOS	15
SAMSKIP COMMANDER	WILSON ASA	MP	Y	387		4750	1997	BARBADOS	15.5
SAMSKIP KVITBJORN	NOR LINES AS	RR				3900	2015	FAROES	14.3
SAMSKIP KVITNOS	NOR LINES AS	RR				4900	2015	FAROES	14.3
SKALAR	UNITED FEEDER SERVICE LTD	CC	N	1 036	257	13 000	2012	PORTUGAL	19
SKYLIGHT (IDUNA)	SEA CONNECT UAB	CC	N	801	200	8820	2007	CYPRUS	18
SONDERBORG	X-PRESS FEEDERS	CC	N	1085	250	14222	2012	MADEIRA	19
SPICA J	BG FREIGHT LINES BV	CC	N	974	170	11 186	2007	ANTIGUA AND BARBUDA	18
SPIRIT	UNIFEEDER A S	CC	N	809	200	9 400	2005	NETHERLANDS	19
Thea II	UNKNOWN	CC	N	340	40	3950	1995	CYPRUS	14.5
THETIS D	UNIFEEDER A S	CC	N	1 421	300	17 882	2009	CYPRUS	20
THULELAND	SWEDISH ORIENT	RR				15960	2006	SWEDEN	19.5
TUNADAL	UNIFEEDER	CC	N	1025	249	13425	2012	MALTA	18
TUNDRALAND	SWEDISH ORIENT	RR				13800	2007	SWEDEN	19.5
VEGA HERCULES	UNIFEEDER A S	CC	Y	966	252	11 500	2006	LIBERIA	18
VERA RAMBOW	UNITED FEEDER SERVICE LTD	CC	N	1 425	300	17 861	2008	GERMANY	20
X-PRESS MULHACEN	SEA CONSORTIUM	CC	N	505	300	9620	2008	MALTA	18.5

Table A.6: Current feeder ships, data retrieved from CMA CGM, Maersk, Samskip and Clarksons 25-05-2021 - 06-06-2021 [14–16, 33]

B
Data retrieved

B.1. Determination of destination ports via container flows

Without the access to commercial datasets such as from Alphaliner, an open source dataset provided by Eurostat is used. Eurostat's data is provided by reporting ports, who for the most part have tallied up all of the comings and goings of containers entering and leaving the port by sea. It is up to each port to determine when they release their totals, but measuring the container flows is done the same for all reporting entities. The main problem which occurs whilst using data provided by Eurostat is that the reporting entity does not specify the exact port from where goods originate from. Regions are given as an origin for goods. The way to circumvent this problem is shown later in the next paragraph.

The database provided by Eurostat is used to determine the number of containers flowing through the network from origin ports to destination ports, as well as the choice of ports taken into account. Firstly, countries are selected by their proximity to the Baltic Sea and the North Sea as maritime partners. Reporting regions taken into account are: Denmark, Estonia, Latvia, Lithuania, Poland, Finland, Sweden (Baltic), Sweden (North Sea), Norway, Russia: Baltic Sea (Gulf of Finland), Russia: Baltic Sea (Non-Gulf of Finland). Partner countries are: The Netherlands, Belgium, and Germany (North Sea). Ports are chosen based of these regions, however there is a difference in data retrieval. Ports situated in countries in the European Union (or were part of) can be selected separately. Ports situated outside of the EU will have to be chosen based on flows the other way around (from partner to reporting). Ports designated as main ports and a destination of containers are all taken into account. If any of these lack containers from any of the origin countries (Belgium, the Netherlands and Germany) for the years of 2010-2020, then these will be taken out of the dataset. Furthermore, it is seen that for Scandinavian and Baltic countries, containers have predominantly an origin in the Netherlands and Germany (North Sea). As a consequence, flows from the remaining regions are omitted from the dataset. To check if any further ports should be taken out of the dataset, the total containers inwards are summed. Ports where zero containers ended up, or have consistent single digit container arrivals across a quarter are now taken out.

This results in a set of 70 ports spread out between Norway in the West and Russia in the East. Note that ports which are situated in the Russian Federation are not taken separately into account, as the data for these are aggregated and given per region. The data for this is found by selecting outward container demand for the main transshipment ports from the regions in the paragraph above. These ports are: Bremerhaven, Hamburg and Rotterdam. The assumption is that the ports which make up the region's demand are Kaliningrad for Baltic Sea (excluding Gulf of Finland) and Bronka, Ust-Luga and Sint Petersburg for the Gulf of Finland. These are by far the largest ports in these two regions and are therefore the main attractors of container demand.

B.2. Chosen ports and information

Port	**Draft** [m]	Sources
Aalborg	10.4	http://harboursreview.com/port-aalborg.html
Åhus	7.6	https://www.ahushamn.se/en/the-port-of-ahus-facts-and-figures/
Ålesund	8.5	https://shipnext.com/port/58278d27b20beb0a70c07db3
Århus	14	http://web.archive.org/web/20190414082335/https://www.Århushavn.dk/en/ terminals/container_terminal/container_terminal.htm
Bergen	12.2	https://www.findaport.com/port-of-bergen#:~:text=Port%20is%20compliant.-, MAX.,Passengers%3A%20Depth%2012.2%20m.
Bremanger	9	http://www.bremangerhamn.no/#text-10
Bronka, St Petersburg,	14.4/ 11.5/ 9.63-11.0	https://port-bronka.ru/en/about-harbor/ http://www.worldportsource.com/ports/commerce/RUS_Port_of_St_Petersburg_61.php
Drammen	11.0/7.5	https://drammenhavn.no/tjenester/fasiliteter/
Egersund	9	https://enhkf.no/en/harbour/harbour-map/
Esbjerg	9.5	https://portesbjerg.dk/en/port-facilities/details
Florø/Flora	12.2	https://www.findaport.com/port-of-floro
Fredericia (Og Shell-Havnen)	15	https://www.adp-as.dk/en/cargo-solutions/container/
Fredrikstad	12	http://www.4allports.com/port-infrastructure-borg-havn—fredrikstad-norway-pid173.html
Gävle	10.1	https://shipnext.com/port/gavle-segvx-swe
Gdansk	15	https://www.portgdansk.pl/en/about-port/terminals-and-quays/deepwater-container-terminal-gdansk/
Gdynia	15.5/11	https://www.gct.pl/en/terminal/
Göteborg	16	https://www.apmterminals.com/en/gothenburg/about/our-terminal
Halmstad	11	https://www.hallandshamnar.se/vara-produktomraden/container/
HaminaKotka	10	http://www.4allports.com/port-infrastructure-hamina-kotka-finland-pid188.html
Hanko	13	https://www.esitteemme.fi/port_of_hanko_ltd/WebView/
Hargshamn	12.3	https://www.hargshamn.se/hamnen/?id=0
Haugesund	10.0-18.0	https://karmsundhavn.no/forretningsomrader/haugesund-cargo-terminals/containers/
Helsingborg	11.7/8.5	https://www.port.helsingborg.se/wp-content/uploads/2021/06/PortInstallations2021.pdf
Helsinki	12	https://www.rauanheimo.com/en/vuosaari-harbour-in-helsinki/
Kaliningrad	10.5	http://www.worldportsource.com/ports/commerce/RUS_Port_of_Kaliningrad_1533.php
Kalmar	4.9 - 6.1	http://www.worldportsource.com/ports/portCall/SWE_Port_of_Kalmar_364.php
Kalundborg	15.0/9.5	https://www.europeanceo.com/finance/the-port-of-kalundborg-proves-still-waters-run-deep/
Karlshamn	10,4	https://www.karlshamnshamn.se/en/containers
Kemi	11.4	https://vayla.fi/documents/25230764/35410858/Ajos+10+m.pdf/b830eedb-4147-4121-9d10 -29f21c0e4a51/Ajos+10+m.pdf?t=1583927708065
Klaipeda	11.5	https://www.terminalas.lt/galimybes-paslaugos?lang=en
Københavns Havn	10	https://www.cmport.com/services/containers/
Kokkola	9.5/9.5/8.3	https://portofkokkola.fi/en/ports/general-port/
Kristiansand S	8.5	https://www.portofkristiansand.no/en/om-oss/kai-og-terminaler/caledonien/
Kristiansund N/Grip	10	http://knhavn.no/wp-content/uploads/2019/03/Welcome-to-the-cruise-port-of-Kristiansund-2019.pdf
Larvik	9.5	https://larvik.havn.no/container/category927.html
Malmö	8.4	https://www.cmport.com/services/containers/
Måløy	8.1-13.1/7-10	sailing directions (enroute) Northa and west coasts of norway
Molde	11	https://www.molde-romsdalhavn.no/en/harbor/ports-and-quays
Moss	7.1-9.1	http://www.worldportsource.com/ports/portCall/NOR_Port_of_Moss_3162.php
Norrköping	9.3	https://www.norrkopingshamn.se/en/pampus-container-and-breakbulk-terminal
Oslo	12	https://www.yilport.com/en/ports/default/Oslo-Norway-%7C-Nordic-Terminals/86/0/0
Oulu	9	https://ouluport.com/en/harbours/oritkari/
Oxelösund (ports)	8-9.7	https://www.oxhamn.se/en/about-the-port/
Pietarsaari	7.4-11	https://www.euroports.com/terminal/general-cargo-terminal-pietarsaari-finland/
Piteå	11.5	https://shipnext.com/port/pitea-sepit-swe
Pori	12	https://portofpori.fi/wp-content/uploads/2020/02/port-of-pori_general-presentation-2020_EN.pdf
Porsgrunn, Rafnes, Herøya, Brevik, Skien, Langesund, Voldsfjorden	16	https://www.dfds.com/en/freight-shipping/terminal-services/brevik-terminal
Raahe	8	https://www.raahensatama.fi/en/info/technical-data
Rana	8	http://moiranahavn.no/oversikt.html
Rauma	10	https://portofrauma.com/wp-content/uploads/2020/05/raumansatama_turvallisuusopas7_2015_en.pdf
Riga	15	https://rop.lv/en/node/2
Sillamäe	15.5	https://www.silport.ee/eng/practical-info.html#1006eng
Södertälje	9	https://shipnext.com/port/sodertalje-sodertalje-canal-sesoe-swe
Stavanger	10	https://www.stavangerhavn.no/en/maritim/terminals/risavika/
Stockholm	16.5	https://www.portsofstockholm.com/stockholm-norvik/container-terminal/
Sundsvall	12.3	https://shipnext.com/port/sundsvall-sesdl-swe
Szczecin	9.15	https://www.port.szczecin.pl/en/ports/ports/
Tallinn	12.4-14.5	https://www.ts.ee/en/containers/

Tornio	8	https://shipnext.com/port/tornio-fitor-fin
Trondheim/Flakk	10	https://trondheimhavn.no/en/havn/froya-2/
Uddevalla	10.7	https://www.uddevalla-hamn.se/download/18.227e02a816cdee19e64c8742/1567584480086/Vattendjup%20kajer%2020190827.pdf
Umeå	5.8-11.0	https://kvarkenports.com/about/umea.html
Varberg	10	https://shipnext.com/port/varberg-sevag-swe
Västerås	6.8	https://shipnext.com/port/vasteras-sevst-swe
Ventspils	14.1	https://www.portofventspils.lv/en/port-in-general/

Table B.1: Ports, their allowable drafts and sources

B.3. Ship calculations

B.3.1. Block coefficient determination

The size parameters and their values of the vessel capacities are shown in table 4.3. Only the width, draft and deadweight are retrieved from Clarkson's [33]. The waterline length is approximated by removing a few meters off the length overall given by Clarkson's. Depending on the length overall, more meters were subtracted for a longer vessel than was for a shorter. The block coefficient (C_b) is predominantly determined by the deadweight (DWT) of the vessel. The estimation of the block coefficient is based on the following equation: $C_b = 0.908683 * DWT^{-0.0320423}$ from Papanikolaou [63]. Using the deadweight provided by Clarksons, the block coefficient is estimated for all ships [33]. It is presumed that the block coefficient lies in the range of $0.6 < C_b < 0.7$ of which only the smallest vessel is not affected. From the C_b the volume of the vessel is calculated by multiplying the size parameters and the C_b. Finally, the displacement is calculated by multiplying the volume by 1.025, which represents the density of seawater [tonne/m^3] These values are required to estimate the fuel consumption of each vessel.

It is assumed that without any other notice, the block coefficient calculated by Papanikolaou, is that which used the length between perpendiculars. To make the small adjustment, the displacement calculated in the paragraph above is used, but will be divided by the waterline length, instead of the length between the two perpendiculars. The former will be assumed to be the C_b for the rest of the thesis as it is used for the Holtrop and Mennen calculations.

B.3.2. Specific fuel consumption

The specific fuel consumption (SFC) is needed to calculate the amount of fuel required for an arc between two ports, as well as whilst a ship is not moving but in operation. Figure B.1 shows the SFC for all prime movers [44]. Prime movers used for ships selected for this thesis are 1000 rpm diesel engines, medium speed diesel engines and low speed diesel engines. These are the prime movers of ships chosen to simulate the various ship types [33]. This puts the SFC of these ships in the range of $175 < SFC < 190$ g/kWh.

	Hamburg	Århus	Copenhagen	Fredericia	Kalundborg	Tallinn	Helsinki	Kemi	Kokkola	Oulu	Haminakotka	Pori	Rauma	Tornio	Klaipeda
Hamburg	X	458	482	500	372	1011	1031	1313	1196	1087	1087	1049	1028	1313	799
Århus	458	X	113	69	50										
Copenhagen	482	113	X	143	115	533									323
Fredericia	500	69	143	X	50										
Kalundborg	372	50	115	50	X										
Tallinn	1011		533			X	48		99				285		316
Helsinki	1031					48	X				87				337
Kemi	1313							X	121	62		292	322	121	
Kokkola	1196							121	X	121		204	230	121	
Oulu	1313							62	121	X		292	365	70	
Haminakotka	1087					99	87				X				
Pori	1049							292	204	292		X	45	292	
Rauma	1028					285	302	322	230	365		45	X	322	372
Tornio	1313							121	121	70		292	322	X	
Klaipeda	799		323			316	337						372		X
Riga	621					291	316								
Ålesund	589														
Bergen	452														
Drammen	420														
Egersund	303														
Fredrikstad	394														
Florø/Flora	520														
Haugesund	295														
Kristiansand	295	222													
Kristiansund	657														
Larvik	367														
Maloy	550														
Moss	397														
Oslo	430	260	272	301											
Porsgrunn	380														
Stavanger	376														
Trondheim	734														
Gdansk	748		274			406									117
Gdynia	748		270			402									113
Szczecin	641		163	286											
Russia (Gulf of Finland)	1173					187	171				106				
Russia (non Gulf of Finland)	783		307												110
Ahus	610		137												
Gothenburg	375	151	137	222	153										
Gävle	1007					270	283	366	277	366		136	132	478	
Halmstad	433	99	70		103										
Helsingborg	459	88	22		91										
Malmö	489		20												
Norrköping	853		375			279	300						279		279
Pitea	1250							106	96	118		242	275	106	
Södertälje	850														
Stockholm	904					217	237						173		265
Varberg	395	102	92		110										

Table B.2: Arcs and the distances [NM] between ports: Hamburg-Klaipeda

	Riga	Ålesund	Bergen	Drammen	Egersund	Fredrikstad	Florø/Flora	Haugesund	Kristiansand	Kristiansund	Larvik	Maloy	Moss	Oslo
Hamburg	621	589	452	420	303	394	520	388	295	657	368	550	397	430
Århus									222					260
Copenhagen														272
Fredericia														301
Kalundborg														
Tallinn	291													
Helsinki	316													
Kemi														
Kokkola														
Oulu														
Haminakotka														
Pori														
Rauma														
Tornio														
Klaipeda														
Riga	X													
Ålesund		X								80		39		
Bergen			X				62	76						
Drammen				X		64					64		28	50
Egersund					X				87					
Fredrikstad				64		X					43		41	70
Florø/Flora			62				X					26		
Haugesund			76					X						
Kristiansand					87				X					163
Kristiansund		80								X				
Larvik				64		43					X		45	74
Maloy		39					26					X		
Moss				28		41					45		X	32
Oslo				50		70			163		74		32	X
Porsgrunn									99		33			98
Stavanger					62			35						
Trondheim										97				
Gdansk														
Gdynia														
Szczecin														
Russia (Gulf of Finland)														
Russia (non Gulf of Finland)	324													
Ahus														
Gothenburg						122			136		114		130	163
Gävle														
Halmstad														
Helsingborg														
Malmö														
Norrköping	267													
Pitea														
Södertälje														
Stockholm														
Varberg														

Table B.3: Arcs and the distances [NM] between ports: Riga-Oslo

	Porsgrunn	Stavanger	Trondheim	Gdansk	Gdynia	Szczecin	Russia (Gulf of Finland)	Russia (non gulf of Finland	Ahus	Gothenburg	Gävle	Halmstad
Hamburg	380	376	734	748	748	641	1173	783	610	375	1007	433
Århus										151		99
Copenhagen				274	270	163		307	137	137		70
Fredericia						286				222		
Kalundborg										153		103
Tallinn				406	402		187				270	
Helsinki							171				283	
Kemi											366	
Kokkola											277	
Oulu											366	
Haminakotka							106					
Pori											136	
Rauma											132	
Tornio											478	
Klaipeda				117	113			110				
Riga								324				
Ålesund												
Bergen												
Drammen												
Egersund		62										
Fredrikstad										122		
Florø/Flora												
Haugesund		35										
Kristiansand	99									136		
Kristiansund			97									
Larvik	33									114		
Maloy												
Moss										130		
Oslo	98									163		
Porsgrunn	X									123		
Stavanger		X										
Trondheim			X									
Gdansk				X	12	240		67	180			
Gdynia				12	X	236		63	190			
Szczecin				240	236	X			157			
Russia (Gulf of Finland)							X					
Russia (non Gulf of Finland)				67	63			X			437	
Ahus				180	190	157			X			
Gothenburg	123	51								X		
Gävle								437			X	
Halmstad												X
Helsingborg												49
Malmö						164			135			76
Norrköping				304	300	387		319	289		257	
Pitea											318	
Södertälje											232	
Stockholm											150	
Varberg										51		43

Table B.4: Arcs and the distances [NM] between ports:Porsgrunn-Halmstad

	Helsingborg	Malmö	Norrköping	Pitea	Södertälje	Stockholm	Varberg
Hamburg	459	489	853	1250	850	904	395
Århus	88						102
Copenhagen	22	20	375				92
Fredericia							
Kalundborg	91						110
Tallinn			279			217	
Helsinki			300			237	
Kemi							
Kokkola				96			
Oulu				118			
Haminakotka							
Pori				242			
Rauma			279	275		173	
Tornio				106			
Klaipeda			279			265	
Riga			267				
Ålesund							
Bergen							
Drammen							
Egersund							
Fredrikstad							
Florø/Flora							
Haugesund							
Kristiansand							
Kristiansund							
Larvik							
Maloy							
Moss							
Oslo							
Porsgrunn							
Stavanger							
Trondheim							
Gdansk			304				
Gdynia			300				
Szczecin		164	387				
Russia (Gulf of Finland)							
Russia (non Gulf of Finland)			319				
Ahus		135	289				
Gothenburg							
Gävle			257	318	232	150	
Halmstad	49	76					43
Helsingborg	X	30					71
Malmö	30	X					
Norrköping			X		92	152	
Pitea				X			
Södertälje			92		X	114	
Stockholm			152		114	X	
Varberg	71						X

Table B.5: Arcs and the distances [NM] between ports: Helsingborg-Varberg

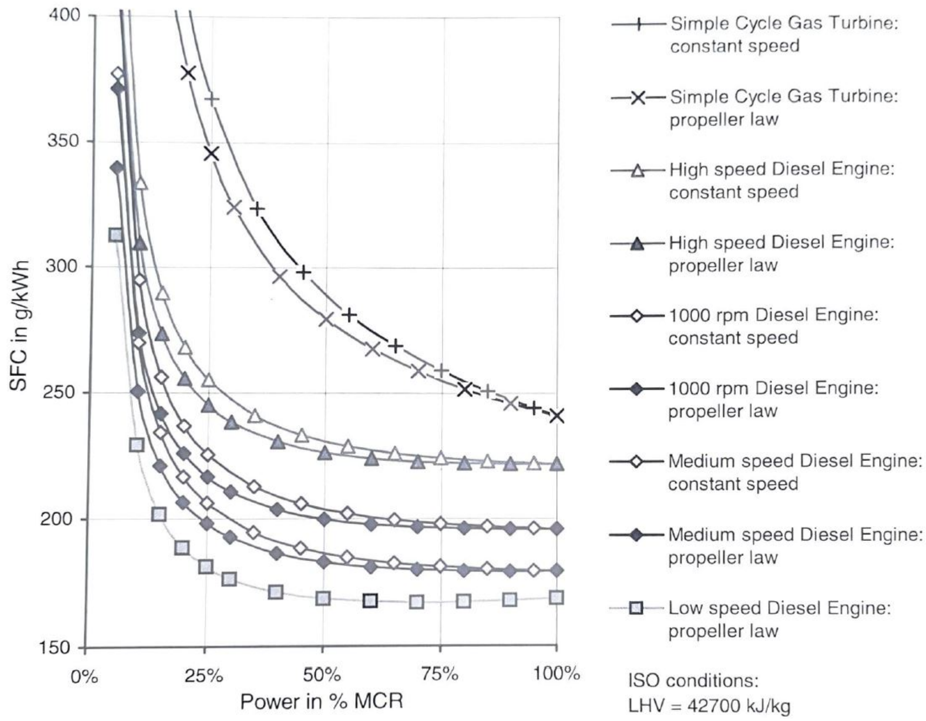

Figure B.1: Specific fuel consumption of prime movers [44]

B.4. Port costs

Another important part of the voyage costs are the costs brought on by entering ports and canals. Port costs are dependant on the gross tonnage (GT) of each ship and which port they are entering. Using the port costs of the port authority of Rotterdam, port tariffs are made up of a base cost, and then reductions are applied if applicable. The base cost of the tariffs are made up between port dues related to the size of the ship and the port dues related to the cargo. For the ship related costs, a ship factor is multiplied by the GT of the ship. For the cargo related costs, a cargo factor is multiplied by the GT of the ship and a switch percentage based on the type of ship. The latter is normally put next to another calculation and seen what the least is, and that is applied. However, it is assumed that no transshipment, or little transshipment takes place, so is not applied here. For feeder container ships, or those on a short sea service, the switch percentage is 50.3 % and the GT tariff is €0.185 per GT. The cargo tariff is €0.468 per TEU [66]. Note that the total costs accumulated by entering the port of Rotterdam are given in Euros. The total cost of the system is to be calculated in US Dollars. This means that a conversion is to be made beforehand.

Hamburg is also chosen for a baseline in port tariffs. Similarly to Rotterdam, costs are built up around the GT of the ship and the cargo handled. However, for the GT part of the calculation, an environmental rate is added. The rates are split up between different sizes of feeder ships. These rates are seen in table B.6.

GT size	**Handling containers** € / loaded TEU	**GT** € / GT	**Environment** € / GT
<= 4,000 GT	0.0578	0.0276	0.0069
<= 30,000 GT	0.1227	0.0582	0.0145
<= 50,000 GT	0.1287	0.0611	0.0153

Table B.6: Base port tariffs for container ships Hamburg [9]

Although both the port authority's data can be used, a further port authority is checked which is situated further from the major hubs. The port authority of Riga's port tariffs are also included. The main tariffs levied for container ships are those for entering the canal. As no other costs are levied for container ships in the document provided, it can be assumed that these are the only costs to be levied, other than sanitary dues and

the dues for port services. For the port of Riga a tariff is levied of €0.409 per GT. Berthing dues are chosen for ’other vessels’, which amount to €0.09 per GT. Sanitary costs for container ships are chosen for ’other vessels’, which are €0.062 per GT. It is assumed that only unmooring and mooring costs are included, although other services may be in need of for the larger feeder ships. These charges are €0.17 per GT.
[35].

Ports	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Aalborg	-	-	-	-	-	23	314	308	984	456
Åhus	-	-	5 566	6 342	5 542	6 288	3 997	-	-	-
Ålesund	18 946	16 007	15 912	13 516	11 302	6 390	10 073	10 980	12 935	10 811
Århus	49 572	55 485	56 661	62 917	69 969	62 380	80 116	87 251	83 793	85 139
Bergen	7 050	7 019	9 792	8 430	9 265	9 394	9 281	10 116	5 058	8 487
Bremanger	-	-	-	-	-	-	-	-	-	-
Drammen	-	4	23	187	7 475	8 989	-	-	-	-
Egersund	1 571	505	872	1 846	2 346	1 512	2 091	2 171	1 730	2 620
Esbjerg	-	-	28	-	37	-	-	17	39	-
Florø/Flora	1 267	669	711	672	414	190	293	2 017	2 436	419
Fredericia	25 879	31 646	33 970	39 566	29 614	28 114	25 769	28 139	25 501	27 189
Fredrikstad	5 804	4 496	10 669	12 532	12 092	12 388	12 872	13 471	12 652	7 769
Gävle	8 706	10 215	15 759	36 512	41 296	54 636	57 687	6 879	3 286	2 579
Gdansk	36 693	44 828	54 207	51 859	67 807	331 121	106 873	105 391	161 397	130 755
Gdynia	109 756	186 344	249 179	299 503	221 316	177 809	165 547	163 509	119 335	86 515
Göteborg	90 649	125 190	138 073	169 189	120 871	60 074	47 684	53 404	36 598	41 226
Halmstad	9 031	10 221	8 204	13 798	16 023	16 904	20 151	20 785	22 096	17 858
HaminaKotka	132 171	124 008	99 611	94 462	104 139	133 938	86 875	37 313	39 441	35 207
Hanko	2	4	-	-	-	-	-	-	-	-
Hargshamn	-	-	-	-	-	-	-	-	-	-
Haugesund	1 127	999	163	1 578	1 371	2 281	5 547	5 104	3 779	6 169
Helsingborg	-	-	-	-	-	-	24 031	28 246	31 446	19 482
Helsinki	71 179	72 819	73 620	76 331	80 793	80 504	76 417	62 483	36 792	40 888
Husum	-	-	483	-	-	-	-	-	-	-
Iggesund	-	-	-	-	-	-	-	-	-	-
Kalmar	-	114	-	-	-	-	-	-	-	-
Kalundborg	-	1 017	2 711	2 973	3 327	2 899	2 893	1 926	1 702	1 768
Karlshamn	-	-	-	-	-	-	874	851	104	-
Karmsund	-	-	-	-	-	-	-	-	-	-
Kemi	-	2 611	4 407	3 237	4 172	4 557	2 884	3 803	4 982	3 287
Klaipeda	98 762	85 924	71 748	46 518	30 989	47 271	59 805	71 335	39 384	21 813
København	25 647	27 461	25 806	41 283	35 826	44 374	43 914	38 229	36 108	33 916
Kokkola	-	820	300	74	1 555	2 625	4 623	1 018	1 026	1 682
Kristiansand	4 381	6 561	4 810	5 800	8 454	8 854	6 947	7 145	9 096	6 216
Kristiansund	45	147	2 580	2 145	1 239	1 282	1 181	1 367	1 596	2 476
Kvinesdal	-	-	-	-	-	-	-	-	-	469
Larvik	4 294	5 951	5 054	4 859	4 715	7 660	5 786	7 960	7 042	10 965
Liepaja	-	-	-	-	-	-	-	-	-	-
Malmö	8 692	8 543	4 457	4 532	1 700	38	5 764	2 925	199	-
Måløy	2 881	6 074	4 462	6 887	6 402	3 794	5 312	6 436	4 009	7 245
Molde	-	-	-	-	-	-	-	-	-	-
Moss	7 955	5 319	3 166	880	597	1 378	1 490	823	2 190	1 952
Norrköping	10 116	12 065	5 569	10 188	16 562	28 814	29 384	21 794	22 861	21 178
Odense	-	-	-	-	-	-	-	-	-	-
Oslo	44 006	39 622	38 256	37 363	19 932	26 526	36 082	36 866	45 919	34 755
Oulu	8 705	7 843	9 090	6 589	7 934	8 185	9 512	7 213	7 459	5 548
Oxelösund	5 027	2 572	1 710	2 273	573	-	-	-	-	-
Pietarsaari	246	4	-	-	-	-	-	-	-	-
Piteå	1	12	14	201	1 475	5 779	6 493	7 053	5 442	6 182
Pori	9 187	10 348	9 473	7 896	10 021	8 331	8 336	5 661	-	-
Porsgrunn	1 524	1 831	2 850	2 139	2 519	1 155	-	-	381	1 661
Raahe	-	1 757	921	958	167	362	638	200	10	-
Rana	-	-	-	-	5	-	-	-	-	-
Rauma	27 968	22 745	24 369	28 218	38 915	53 443	51 831	37 750	37 020	32 057
Riga	112 894	86 141	85 911	91 553	57 840	55 443	47 784	42 746	59 497	39 517
Russia (Gulf of Finland)	563 022	677 069	666 677	624 314	530 276	402 909	289 091	254 341	181 663	145 034
Russia (non Gulf of Finland)	100 009	89 971	52 823	59 868	56 422	61 958	80 657	83 897	91 859	82 881
Sillamäe	-	-	-	-	-	-	184	2 012	-	-
Södertälje	-	-	9 758	7 311	5 549	1 233	3 106	3 749	2 857	4 095
Stavanger	2 072	7 325	1 170	3 594	-	-	9 751	4 558	3 562	4 912
Stockholm	12 729	10 508	6 751	14 158	14 708	12 016	19 312	13 842	10 535	3 034
Sundsvall	-	-	-	-	-	-	-	-	-	-
Sveagruva	-	-	-	-	-	-	-	-	-	-
Svelgen	-	-	-	-	-	-	-	-	-	-
Swinoujscie	-	-	-	-	-	-	-	-	-	-
Szczecin	19 016	19 339	18 232	22 450	22 493	25 618	20 766	19 820	21 918	18 320
Tallinn	82 979	63 662	67 980	57 843	35 823	26 871	32 062	34 966	28 734	23 335
Tornio	2 006	3 706	3 000	2 428	1 837	2 310	2 186	2 452	1 768	1 747
Tromsø	-	-	-	-	-	-	-	-	-	-
Trondheim	1 416	1 246	511	406	629	1 351	1 019	1 545	1 012	1 354
Turku	6 202	5 395	507	-	-	-	-	-	-	-
Uddevalla	36	14	28	5	-	-	-	-	-	-
Umeå	-	-	-	-	-	-	-	-	-	-
Vaasa	-	-	-	-	-	-	-	-	-	-
Varberg	-	-	-	-	-	-	5 238	-	-	-
Västerås	1 862	1 987	1 078	-	-	-	-	-	-	-
Ventspils	-	-	-	-	-	-	-	162	-	-
Verdal	-	40	-	-	-	-	-	-	-	-
Total	1 733 083	1 906 203	1 909 682	1 988 183	1 724 328	1 839 971	1 530 523	1 362 029	1 229 233	1 040 968

Table B.7: Container flows between German North Sea ports and chosen destination ports

Ports	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Aalborg	54362	56062	51373	32148	29773	31069	29167	19604	31345	32184
Åhus	0	0	10204	8451	6929	8146	6855	7034	5223	4990
Ålesund	31935	30760	28664	29696	26372	26183	34117	27385	28961	27144
Århus	216816	202129	203756	213929	222100	223836	250415	270533	281291	310225
Bergen	13725	15372	15167	15495	15835	15601	15037	19057	19935	18987
Bodø	7219	9146	6902	11	0	0	0	2	0	0
Borg	18084	18087	19986	22057	20475	20545	0	0	0	0
Bremanger	774	367	413	704	2246	2414	0	0	0	0
Brønnøy	0	1	0	3	0	0	0	0	0	0
Bronnoysund	0	0	0	0	0	0	0	4	6	0
Drammen	10652	13443	16184	16694	31378	28454	26900	20203	15282	12137
Egersund	2719	1835	2007	3734	3772	2480	4153	3417	3536	4115
Esbjerg	19886	17337	14964	12633	11602	2004	4224	10713	13310	12857
Finland - other ports	0	0	0	0	0	0	0	56	108	0
Florø/Flora	3537	2235	2282	3684	2743	1884	1594	3387	4610	3546
Fredericia	32238	35017	35177	43538	41101	42509	41033	43208	40949	43997
Frederikshavn	0	0	0	0	0	0	0	62	0	0
Fredrikstad	0	0	0	0	0	0	24037	31326	24491	22789
Gävle	55011	52046	57171	64835	57737	74699	102375	101278	87948	85155
Gdansk	331806	464331	591521	612281	511151	772717	728945	854870	889082	808140
Gdynia	298845	324944	367551	472347	325208	296207	287328	365469	385230	384891
Göteborg	459293	463828	447797	425908	398958	409165	322715	375524	377224	382833
Grenå	2	4	0	0	0	0	0	0	0	0
Halmstad	14670	17668	16799	23373	26682	26601	23170	22351	26625	21745
HaminaKotka	254342	271621	270667	250954	234093	282353	312974	297772	307998	286842
Hammerfest	208	224	267	79	11	2	0	161	277	338
Hanko	20	0	0	0	0	0	0	0	26	0
Hargshamn	0	0	483	0	0	0	0	0	0	0
Harstad	0	0	9707	439	85	393	463	323	16	450
Haugesund	0	0	0	0	0	0	14069	14258	14053	14655
Helsingborg	85219	86183	93362	102819	101065	103833	126903	124298	141213	134982
Helsinki	175565	187528	187425	189302	210906	215194	232378	247011	250578	234957
Husum	0	0	0	10	0	0	54	0	0	0
Iggesund	0	0	1632	8753	11008	11483	14190	8740	14918	12712
Kalmar	0	114	0	0	0	0	0	0	0	0
Kalundborg	0	1033	2711	3039	3327	2990	2893	1947	1702	2074
Karlshamn	0	0	0	669	0	160	5387	4766	772	0
Karlskrona	13	118	4760	40	113	9	51	28	81	93
Karmsund	3632	3469	1791	4178	7211	8981	0	0	0	0
Kemi	2	3126	4707	3524	8603	8183	5918	7214	8923	5447
Klaipeda	194301	194385	201660	228662	175799	226263	240882	382685	353615	319377
Københavns	73931	75962	72093	73650	76458	76775	73862	72764	73158	68822
Køge	0	0	0	0	0	0	0	0	182	0
Kokkola	9706	7690	6518	6743	8223	8832	9529	11395	8928	6995
Kristiansand	18748	22371	24125	24186	25510	27414	22951	24950	26027	24068
Kristiansund	6699	5229	7878	9737	10269	9834	9861	9340	8720	9023
Kvinesdal	0	0	0	0	0	0	0	0	0	523
Larvik	34653	32364	32195	31101	30652	29348	35283	38826	40843	38321
Liepaja	2246	2783	2620	2189	1895	1075	1822	1485	1467	2022
Malmö	4952	9319	5903	8391	7713	6149	8837	7903	8495	8968
Måløy	17911	16918	15724	11786	13408	10193	16522	12084	9877	10542
Mo i Rana	0	0	0	0	0	0	53	0	345	3208
Molde	38	100	48	75	6	0	0	341	51	111
Mosjøen	0	0	6447	9956	11466	11501	11970	16215	19855	16739
Moss	34278	34379	33924	29920	34981	29982	29961	24788	27705	29697
Narvik	38	30	0	0	0	0	0	0	0	0
Norrköping	23417	21570	20928	23520	21968	37695	53889	51260	51274	51706
Norrtälje	0	0	0	0	0	0	0	0	51274	51706
Odense	0	0	0	0	0	0	1080	0	0	0
Oskarshamn	0	0	0	44	0	0	0	0	0	0
Oslo	110788	107525	107817	115221	102874	108935	110226	124901	134369	136779
Oulu	11240	13957	11142	7004	13404	13058	15875	18744	15380	10396
Oxelösund	9139	7098	3448	6583	7198	5789	6334	4929	5212	4810
Pietarsaari	256	4	0	0	0	0	0	0	1	0
Piteå	253	715	533	3132	7471	10160	9281	9111	7758	8185
Pori	9399	12688	14159	14556	11123	8463	8423	5883	164	294
Porsgrunn	7980	11310	12054	15553	15288	14123	12126	11691	13523	14118
Raahe	2168	1757	933	958	169	363	643	200	10	3
Rana	341	308	345	242	121	139	0	0	0	0
Rauma	89214	97300	111781	124254	116672	114076	123495	115386	115281	93135
Riga	163620	191716	199542	205959	184512	201820	232432	245947	243892	235190
Sillamäe	0	0	18	0	99	906	7364	8326	8559	0
Södertälje	28142	20388	10795	7810	7126	5817	7097	6694	7760	9233
Stavanger	8015	13012	18734	13068	13246	12890	17658	17119	23890	18590
Stockholm	17347	20993	25556	27551	28843	34628	35675	30663	32151	26232
Sundsvall	9466	11780	11377	11576	9619	13472	23030	18941	19705	21794
Sveagruva	3553	2907	0	272	153	34	8	0	0	311
Svelgen	0	0	0	0	0	0	2577	2912	2715	6175
Sweden - other ports	0	0	3120	3440	3924	3801	4939	3702	3741	3492
Swinoujscie	134	14	391	0	339	2224	4398	3036	826	440
Szczecin	26787	28469	31284	32941	32841	43634	43828	38827	38156	45855
Tallinn	107761	121984	132323	131845	106811	103156	110919	113963	111534	109308
Tornio	7353	9279	8399	7904	7119	7742	6832	6852	6098	6484
Tromsø	6563	7667	6216	74	78	166	1275	925	1636	4218
Trondheim	6280	7663	8755	10220	8703	8626	8938	8850	7275	8738
Turku	6220	5420	507	0	4	0	0	499	562	465
Uddevalla	43	33	75	5	3	688	718	168	0	0
Umeå	3228	4164	5333	4243	1887	10868	14609	13683	15595	15483
Vaasa	0	0	0	0	2	0	19	0	0	0
Varberg	4020	3872	4225	5237	5397	5832	11588	6632	7930	11206
Västerås	12050	10254	8060	5710	6776	7574	8326	7439	8523	9360
Ventspils	0	0	36	0	0	117	200	992	139	100
Verdal	9061	10543	0	0	0	0	0	0	0	0
Visby	0	0	0	0	0	0	74	0	0	0
Ystad	0	0	1	0	0	0	0	0	0	0
Total	3171914	3423948	3632452	3780645	3420634	3832257	3962754	4363052	4489914	4310507

Table B.8: Total container flows [TEU] to selected ports for 2011-2020

200	400	600	800	1000	1200	1400	1600
Ålesund	Århus	Århus	Århus	Århus	Århus	Århus	Gdansk
Århus	Fredericia	Gdansk	Gdansk	Gdansk	Gdansk	Gdansk	Gdynia
Fredericia	Gävle	Gdynia	Gdynia	Gdynia	Gdynia	Gdynia	Russia (Gulf of Finland)
Gävle	Gdansk	Göteborg	Göteborg	Göteborg	Göteborg	Russia (Gulf of Finland)	Russia (non Gulf of Finland)
Gdansk	Gdynia	HaminaKotka	HaminaKotka	HaminaKotka	HaminaKotka	Russia (non Gulf of Finland)	
Gdynia	Göteborg	Helsinki	Helsinki	Helsinki	Russia (Gulf of Finland)		
Göteborg	HaminaKotka	Klaipeda	Klaipeda	Riga	Russia (non Gulf of Finland)		
Halmstad	Helsinki	Copenhagen	Riga	Russia (Gulf of Finland)			
HaminaKotka	Klaipeda	Oslo	Russia (Gulf of Finland)	Russia (non Gulf of Finland)			
Helsingborg	Copenhagen	Rauma	Russia (non Gulf of Finland)				
Helsinki	Norrköping	Riga					
Klaipeda	Oslo	Russia (Gulf of Finland)					
Copenhagen	Rauma	Russia (non Gulf of Finland)					
Norrköping	Riga	Tallinn					
Oslo	Russia (Gulf of Finland)						
Rauma	Russia (non Gulf of Finland)						
Riga	Szczerin						
Russia (Gulf of Finland)	Tallinn						
Russia (non Gulf of Finland)							
Stockholm							
Szczerin							
Tallinn							

Table B.9: Ports included per step of minimum inflow

C
Results

C.1. Verification results

Node i	Node j	Trips	Time spent at sea [h]	Time spent in port [h]	Time Total on arc [h]	Fuel use sea[kg]	Fuel use port [kg]	Fuel cost [$]	Port Fees [$]	Total costs per arc [$]
Hamburg	Århus	13	356.2	156	512.2	148350.176	17097.6	33089.5552	11456.88653	176465.4
Hamburg	Oslo	7	384.5333333	84	468.53333	160150.4427	9206.4	33871.36853	6169.092748	160712.9
Hamburg	Haugesund	2	118.8	24	142.8	49477.824	2630.4	10421.6448	1762.597928	48962.9
Hamburg	Ålesund	3	231.2	36	267.2	96290.176	3945.6	20047.1552	2643.896892	91509.37
Ålesund	Trondheim	1	19.4	12	31.4	8079.712	1315.2	1878.9824	881.298964	10847.46
Århus	Hamburg	13	356.2	156	512.2	148350.176	17097.6	33089.5552	1085.886224	166094.4
Oslo	Hamburg	8	439.4666667	96	535.46667	183029.0773	10521.6	38710.13547	668.237676	177289.7
Haugesund	Hamburg	2	118.8	24	142.8	49477.824	2630.4	10421.6448	167.059419	47367.36
Ålesund	Hamburg	1	77.06666667	12	89.066667	32096.72533	1315.2	6682.385067	83.5297095	29705.36
Trondheim	Hamburg	1	94.33333333	12	106.33333	39287.94667	1315.2	8120.629333	83.5297095	35590.69
Haugesund	Oslo	1	38.53333333	12	50.533333	16048.36267	1315.2	3472.712533	881.298964	17369.05
Ålesund	Haugesund	1	27.8	12	39.8	11578.144	1315.2	2578.6688	881.298964	13710.6
				Total time [h]	2898.3333				Total costs [$]	975625.2

Table C.1: Time and costs for the verification model for bunker costs of $200 per ton

Node i	Node j	Trips	Time spent at sea [h]	Time spent in port [h]	Time Total on arc [h]	Fuel use sea[kg]	Fuel use port [kg]	Fuel cost [$]	Port Fees [$]	Total costs per arc [$]
Hamburg	Århus	13	356.2	156	512.2	148350.176	17097.6	82723.888	11456.88653	226099.7
Hamburg	Oslo	8	439.4666667	96	535.46667	183029.0773	10521.6	96775.33867	7050.391712	241737.1
Hamburg	Haugesund	2	118.8	24	142.8	49477.824	2630.4	26054.112	1762.597928	64595.36
Hamburg	Ålesund	2	154.1333333	24	178.13333	64193.45067	2630.4	33411.92533	1762.597928	81053.4
Oslo	Haugesund	1	38.53333333	12	50.533333	16048.36267	1315.2	8681.781333	881.298964	22578.12
Haugesund	Ålesund	1	27.8	12	39.8	11578.144	1315.2	6446.672	881.298964	17578.6
Ålesund	Trondheim	1	19.4	12	31.4	8079.712	1315.2	4697.456	881.298964	13665.94
Århus	Hamburg	13	356.2	156	512.2	148350.176	17097.6	82723.888	1085.886224	215728.7
Oslo	Hamburg	7	384.5333333	84	468.53333	160150.4427	9206.4	84678.42133	584.7079665	205935.6
Haugesund	Hamburg	2	118.8	24	142.8	49477.824	2630.4	26054.112	167.059419	62999.83
Ålesund	Hamburg	2	154.1333333	24	178.13333	64193.45067	2630.4	33411.92533	167.059419	79457.87
Trondheim	Hamburg	1	94.33333333	12	106.33333	39287.94667	1315.2	20301.57333	83.5297095	47771.64
				Total time [h]	2898.3333				Total costs [$]	1279202

Table C.2: Time and costs for the verification model for bunker costs of $500 per ton

Node i	Node j	Trips	Time spent at sea [h]	Time spent in port [h]	Time Total on arc [h]	Fuel use sea[kg]	Fuel use port [kg]	Fuel cost [$]	Port Fees [$]	Total costs per arc [$]
Hamburg	Århus	13	356.2	156	512.2	148350.176	17097.6	165447.776	11456.88653	308823.6
Hamburg	Oslo	8	439.4666667	96	535.46667	183029.0773	10521.6	193550.6773	7050.391712	338512.4
Hamburg	Haugesund	2	118.8	24	142.8	49477.824	2630.4	52108.224	1762.597928	90649.48
Hamburg	Ålesund	2	154.1333333	24	178.13333	64193.45067	2630.4	66823.85067	1762.597928	114465.3
Oslo	Haugesund	1	38.53333333	12	50.533333	16048.36267	1315.2	17363.56267	881.298964	31259.9
Haugesund	Ålesund	1	27.8	12	39.8	11578.144	1315.2	12893.344	881.298964	24025.28
Ålesund	Trondheim	1	19.4	12	31.4	8079.712	1315.2	9394.912	881.298964	18363.39
Århus	Hamburg	13	356.2	156	512.2	148350.176	17097.6	165447.776	1085.886224	298452.6
Oslo	Hamburg	7	384.5333333	84	468.53333	160150.4427	9206.4	169356.8427	584.7079665	290614
Haugesund	Hamburg	2	118.8	24	142.8	49477.824	2630.4	52108.224	167.059419	89053.94
Ålesund	Hamburg	2	154.1333333	24	178.13333	64193.45067	2630.4	66823.85067	167.059419	112869.8
Trondheim	Hamburg	1	94.33333333	12	106.33333	39287.94667	1315.2	40603.14667	83.5297095	68073.21
				Total time [h]	2898.3333				Total costs [$]	1785163

Table C.3: Time and costs for the verification model for bunker costs of $1000

C.2. Variation of bunker cost results

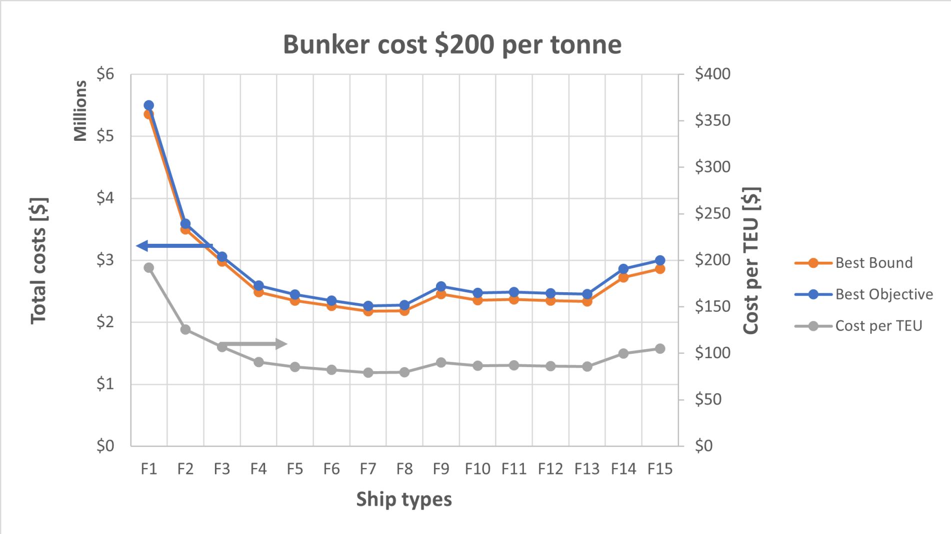

Figure C.1: Total costs [$] for bunker costs of $200 per tonne and cost per TEU [$]

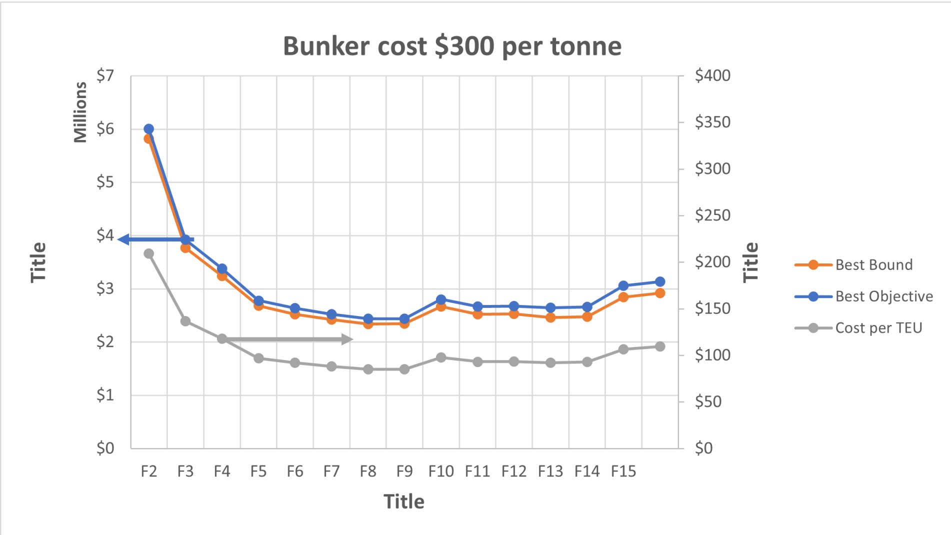

Figure C.2: Total costs [$] for bunker costs of $300 per tonne and cost per TEU [$]

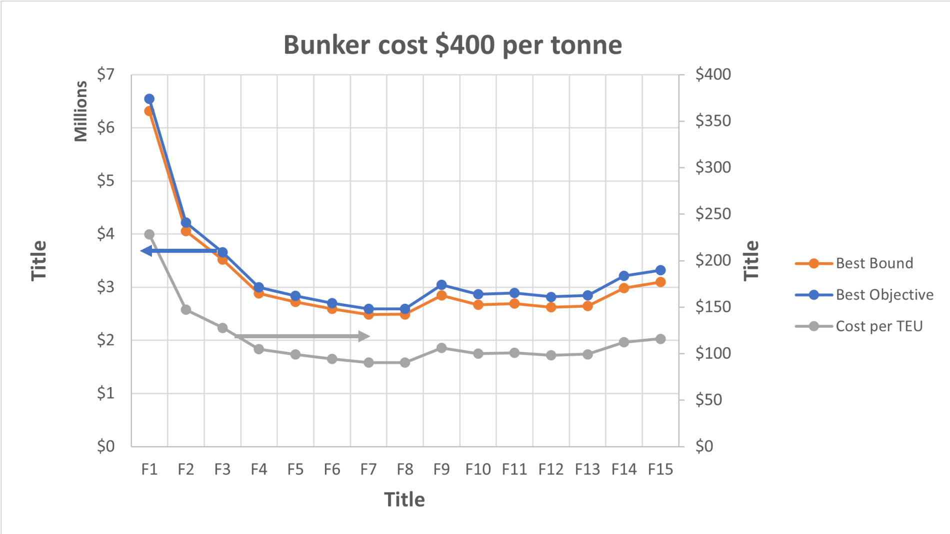

Figure C.3: Total costs [$] for bunker costs of $400 per tonne and cost per TEU [$]

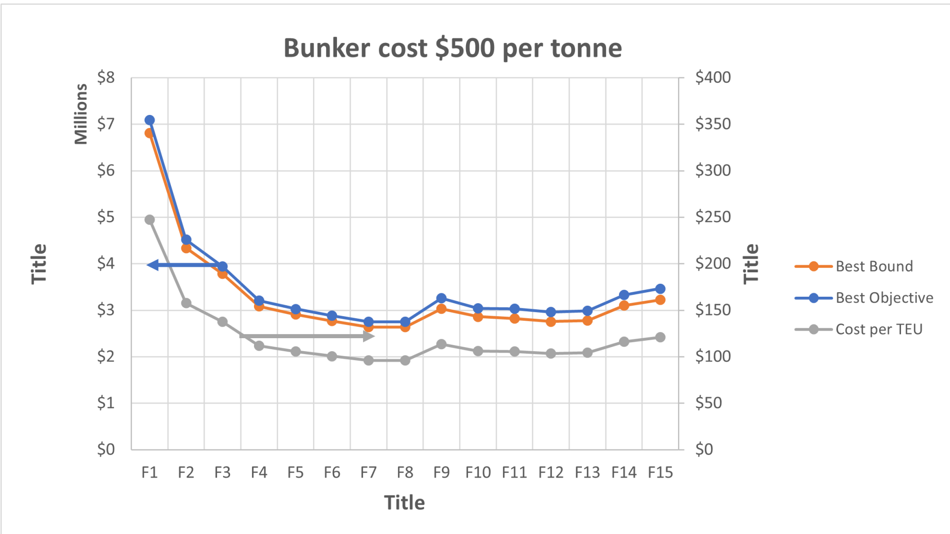

Figure C.4: Total costs [$] for bunker costs of $500 per tonne and cost per TEU [$]

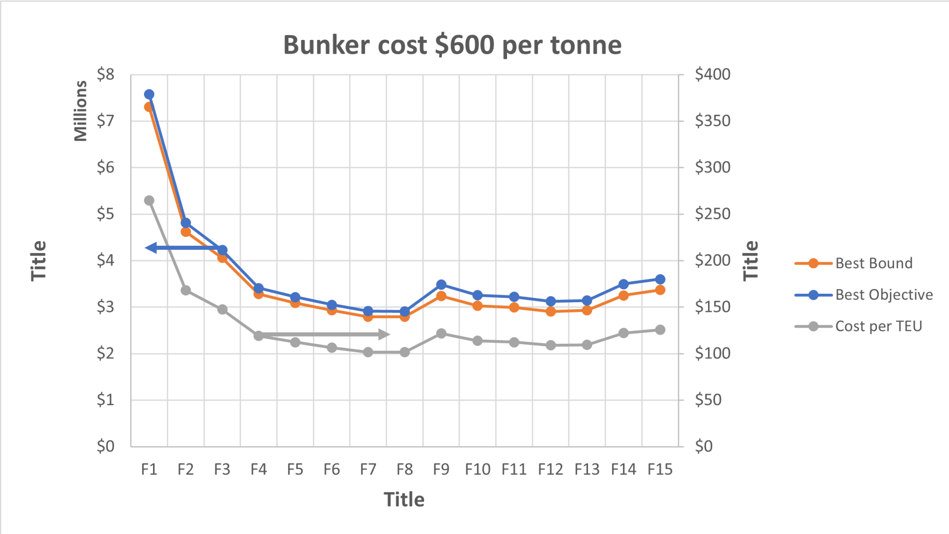

Figure C.5: Total costs [$] for bunker costs of $600 per tonne and cost per TEU [$]

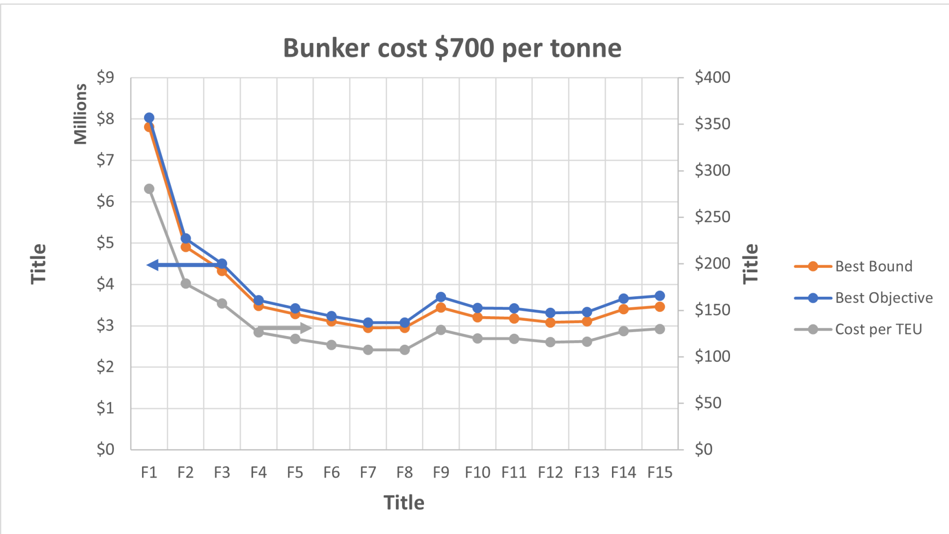

Figure C.6: Total costs [$] for bunker costs of $700 per tonne and cost per TEU [$]

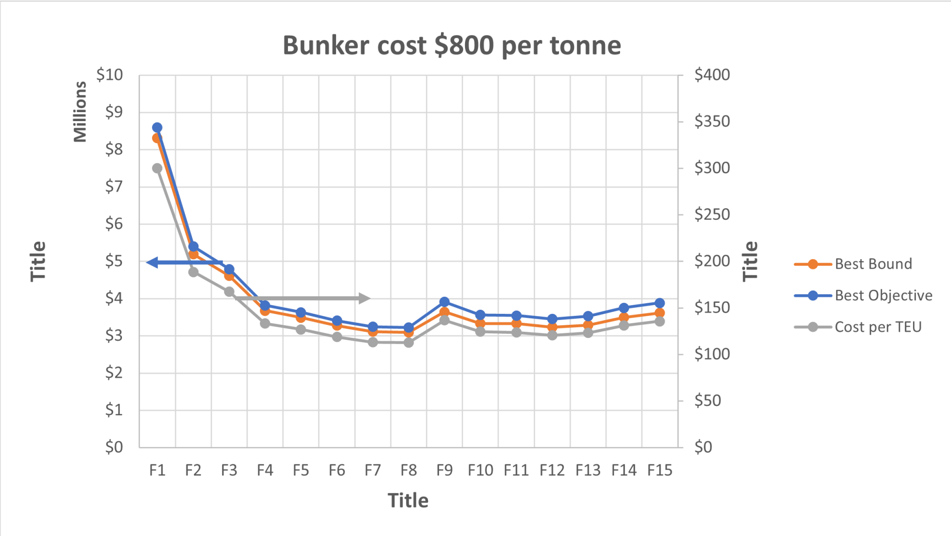

Figure C.7: Total costs [$] for bunker costs of $800 per tonne and cost per TEU [$]

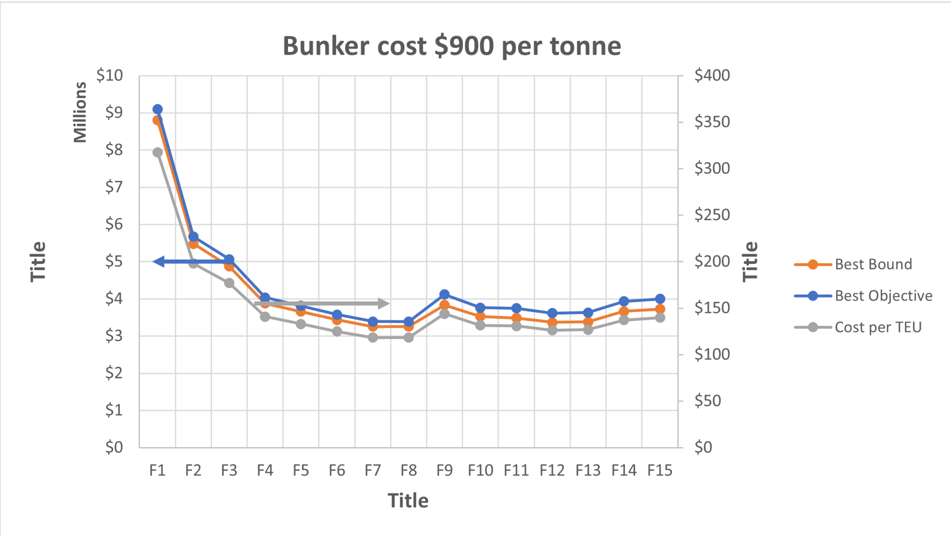

Figure C.8: Total costs [$] for bunker costs of $900 per tonne and cost per TEU [$]

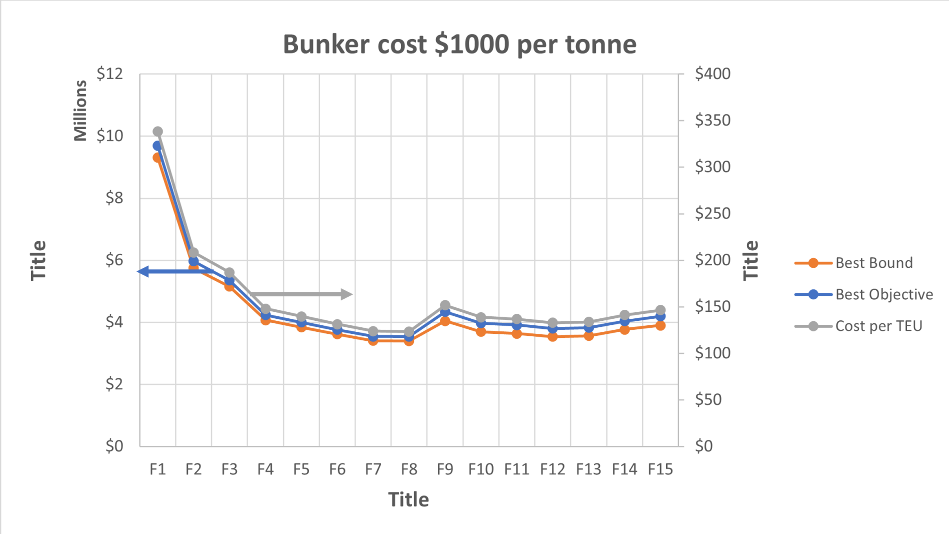

Figure C.9: Total costs [$] for bunker costs of $1000 per tonne and cost per TEU [$]

Table C.4: Total costs per ship type for various bunker costs from $200 to $1000 per tonne

Ships	Bunker cost [$ per tonne] 200	300	400	500	600	700	800	900	1000
F1	$5 750 444.10	$6 290 993.59	$6 825 096.54	$7 369 669.00	$7 902 976.06	$8 449 723.80	$8 976 944.83	$9 526 558.29	$10 061 195.12
F2	$3 773 334.38	$4 082 228.01	$4 388 766.79	$4 694 068.93	$4 998 401.25	$5 318 256.15	$5 614 506.12	$5 923 233.55	$6 238 102.88
F3	$3 215 611.73	$3 508 071.23	$3 806 376.32	$4 107 880.74	$4 406 069.46	$4 713 296.91	$5 006 681.65	$5 305 241.75	$5 593 484.03
F4	$2 690 275.97	$2 906 904.37	$3 124 941.37	$3 343 428.79	$3 560 556.57	$3 777 044.12	$3 994 893.64	$4 205 402.65	$4 434 999.67
F5	$2 558 985.27	$2 773 337.47	$2 969 146.80	$3 176 793.04	$3 389 434.28	$3 599 252.14	$3 808 977.21	$4 014 444.69	$4 203 156.26
F6	$2 453 147.08	$2 638 016.68	$2 822 671.10	$3 009 566.44	$3 194 496.39	$3 380 388.15	$3 565 799.13	$3 749 617.39	$3 938 063.48
F7	$2 399 583.96	$2 553 666.81	$2 724 502.72	$2 905 627.90	$3 075 717.08	$3 234 646.22	$3 418 899.87	$3 573 234.88	$3 739 224.82
F8	$2 384 464.98	$2 553 186.13	$2 718 977.74	$2 886 615.21	$3 053 674.42	$3 221 701.04	$3 397 316.09	$3 558 313.49	$3 722 068.04
F9	$2 706 566.63	$2 912 168.73	$3 134 487.29	$3 345 199.73	$3 572 672.15	$3 796 992.66	$4 012 475.00	$4 242 033.94	$4 645 334.13
F10	$2 579 642.75	$2 768 050.46	$2 961 294.32	$3 153 041.64	$3 342 899.06	$3 522 460.69	$3 734 794.88	$3 921 066.34	$4 114 614.11
F11	$2 621 916.76	$2 780 012.99	$2 984 569.81	$3 167 230.82	$3 326 842.82	$3 525 111.91	$3 713 705.03	$3 871 626.32	$4 085 878.36
F12	$2 530 561.37	$2 700 038.83	$2 869 514.52	$3 075 100.93	$3 247 108.75	$3 382 069.93	$3 553 388.75	$3 740 719.05	$3 912 147.20
F13	$2 547 425.17	$2 734 350.88	$2 910 225.20	$3 083 189.34	$3 262 012.47	$3 438 572.74	$3 621 526.46	$3 792 483.57	$3 971 332.65
F14	$2 967 827.85	$3 102 820.50	$3 239 070.18	$3 445 812.73	$3 553 823.73	$3 737 253.91	$3 857 025.33	$4 066 380.92	$4 225 562.05
F15	$3 114 486.23	$3 266 903.52	$3 415 196.34	$3 526 312.53	$3 710 397.81	$3 859 880.75	$4 006 178.91	$4 191 771.35	$4 266 586.01

C.3. Increase of container inflow

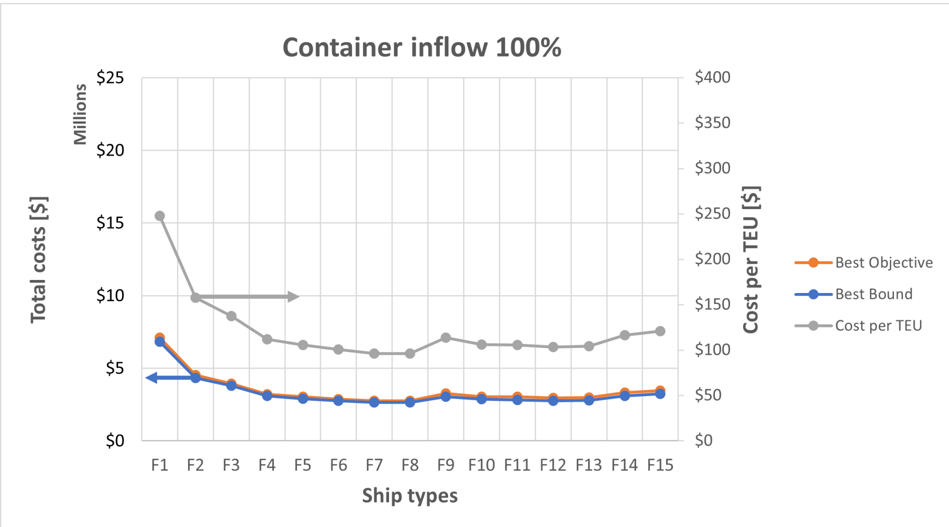

Figure C.10: Total costs [$] for container flows *100% for bunker costs of $500 per tonne and cost per TEU [$]

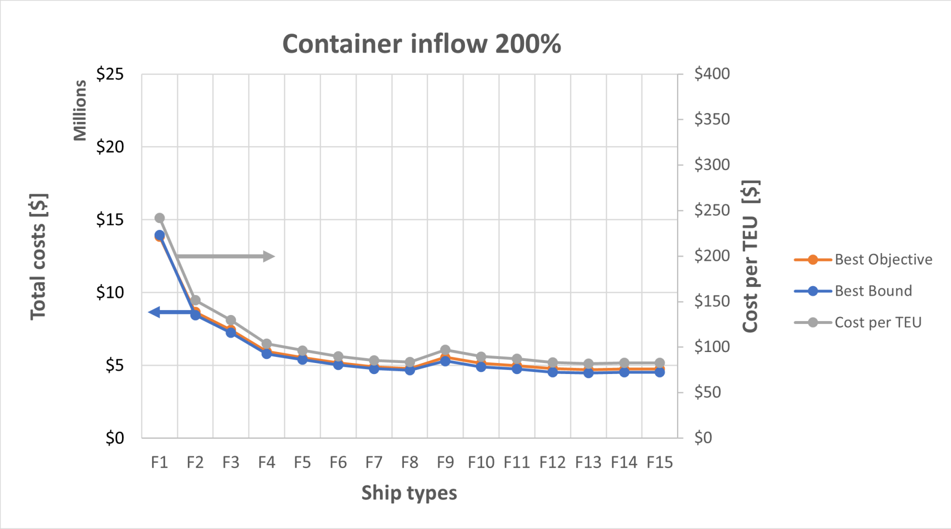

Figure C.11: Total costs [$] for container flows *200% for bunker costs of $500 per tonne and cost per TEU [$]

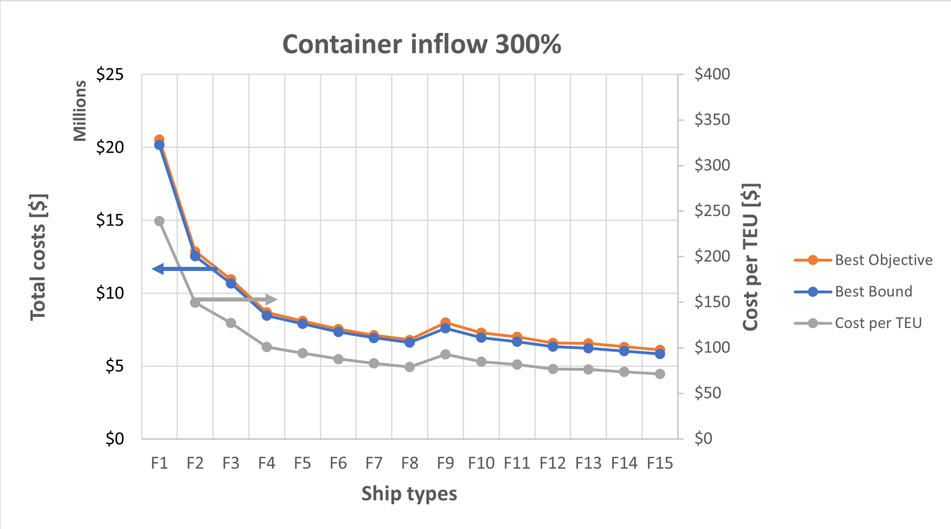

Figure C.12: Total costs [$] for container flows *300% for bunker costs of $500 per tonne and cost per TEU [$]

C.4. Increase of minimum container inflow of ports

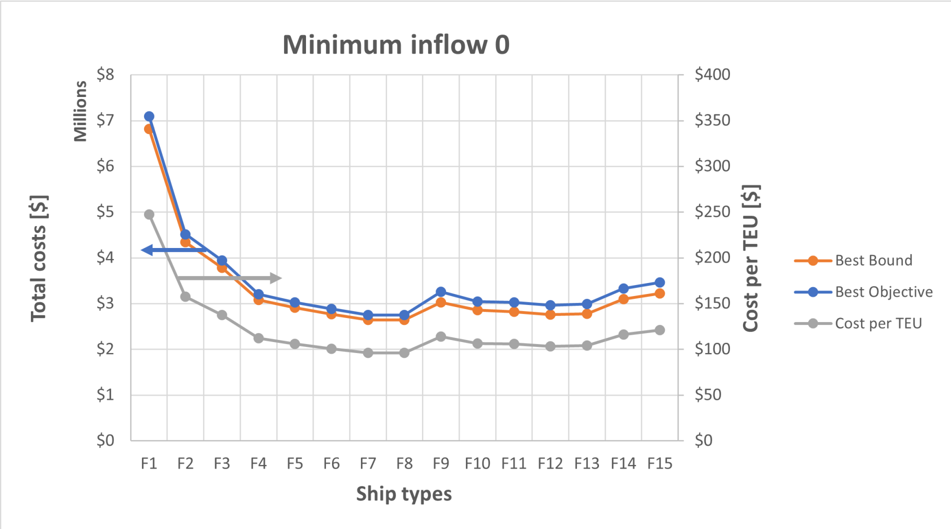

Figure C.13: Total cost [$] for container flows to ports with a minimum inflow of 0 TEU per ship type for bunker costs of $500 per tonne

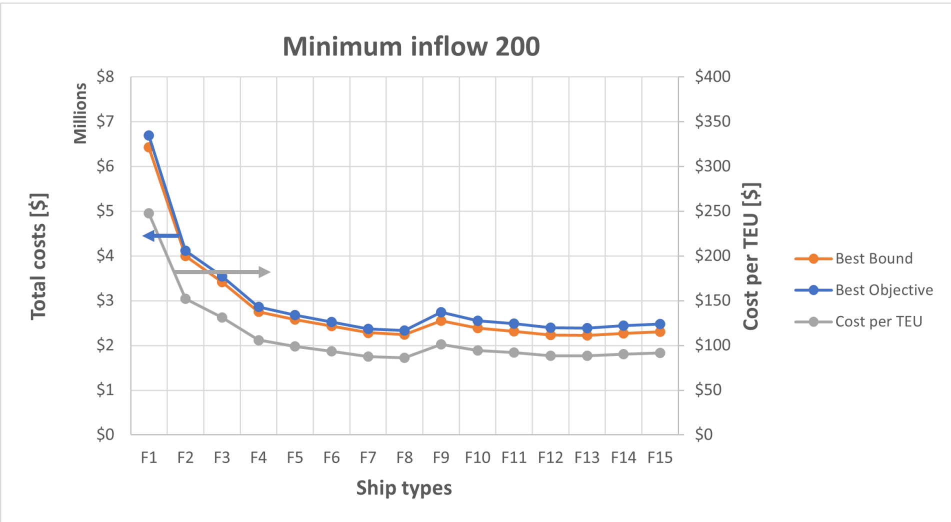

Figure C.14: Total cost [$] for container flows to ports with a minimum inflow of 200 TEU per ship type for bunker costs of $500 per tonne

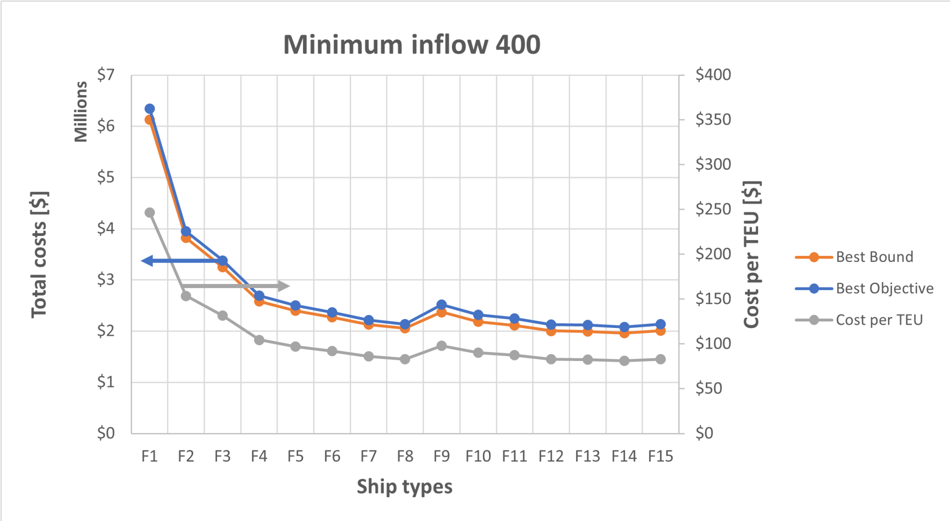

Figure C.15: Total cost [$] for container flows to ports with a minimum inflow of 400 TEU per ship type for bunker costs of $500 per tonne

Figure C.16: Total cost [$] for container flows to ports with a minimum inflow of 600 TEU per ship type for bunker costs of $500 per tonne

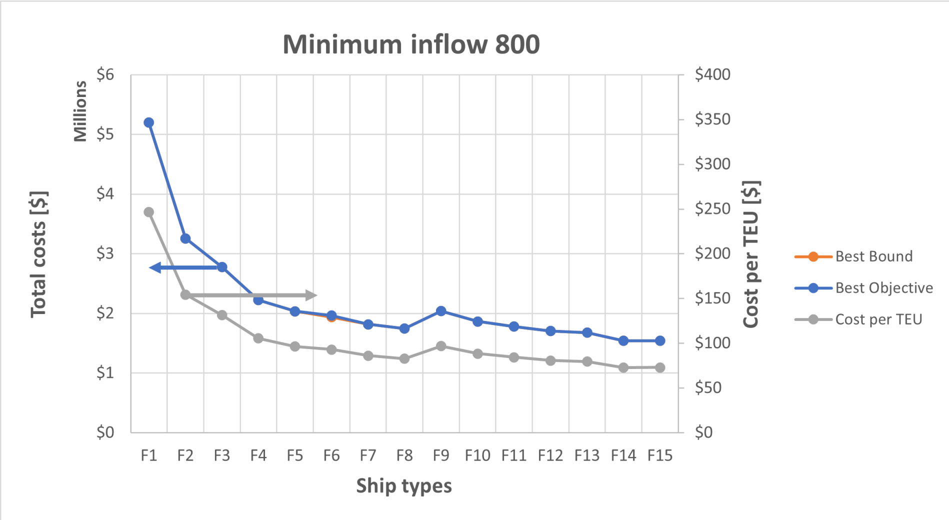

Figure C.17: Total cost [$] for container flows to ports with a minimum inflow of 800 TEU per ship type for bunker costs of $500 per tonne

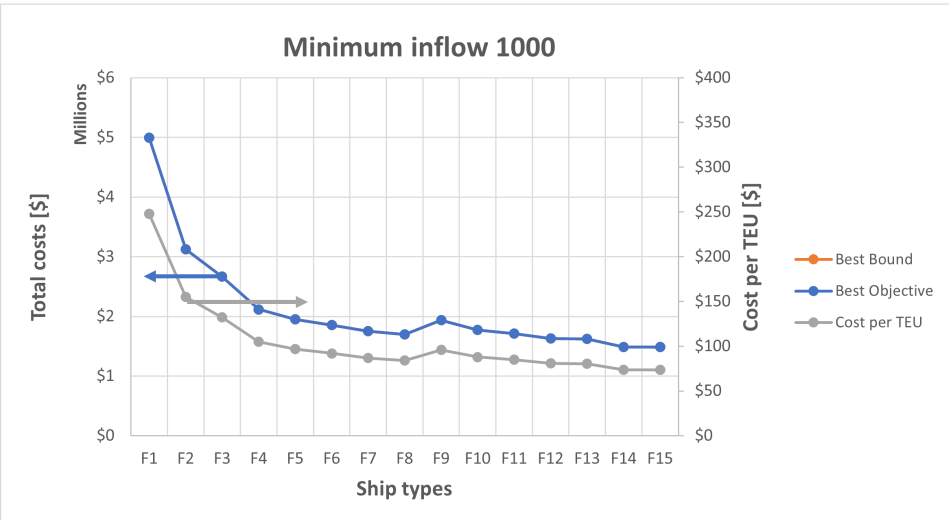

Figure C.18: Total cost [$] for container flows to ports with a minimum inflow of 1000 TEU per ship type for bunker costs of $500 per tonne

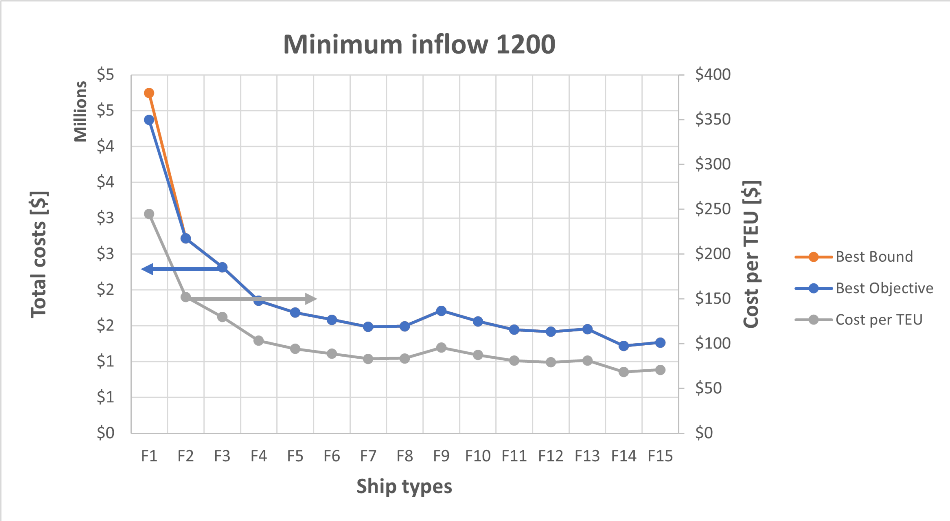

Figure C.19: Total cost [$] for container flows to ports with a minimum inflow of 1200 TEU per ship type for bunker costs of $500 per tonne

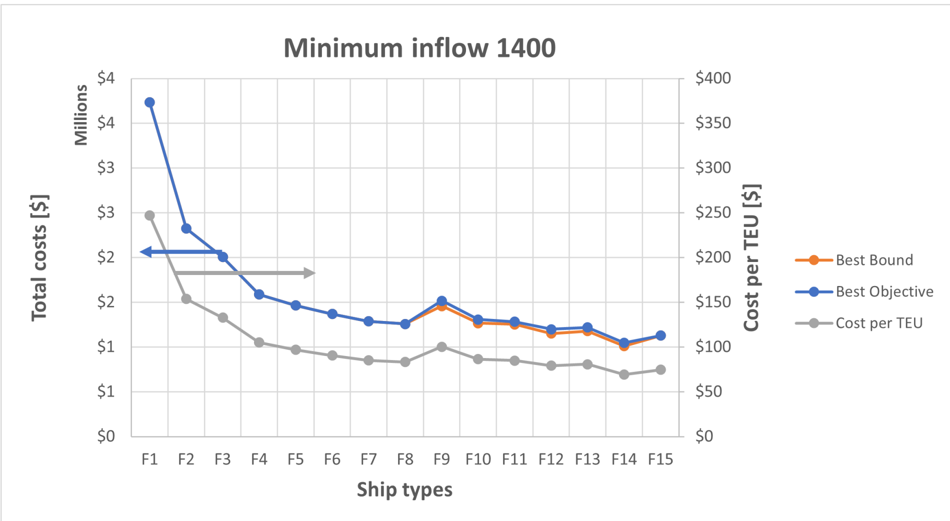

Figure C.20: Total cost [$] for container flows to ports with a minimum inflow of 1400 TEU per ship type for bunker costs of $500 per tonne

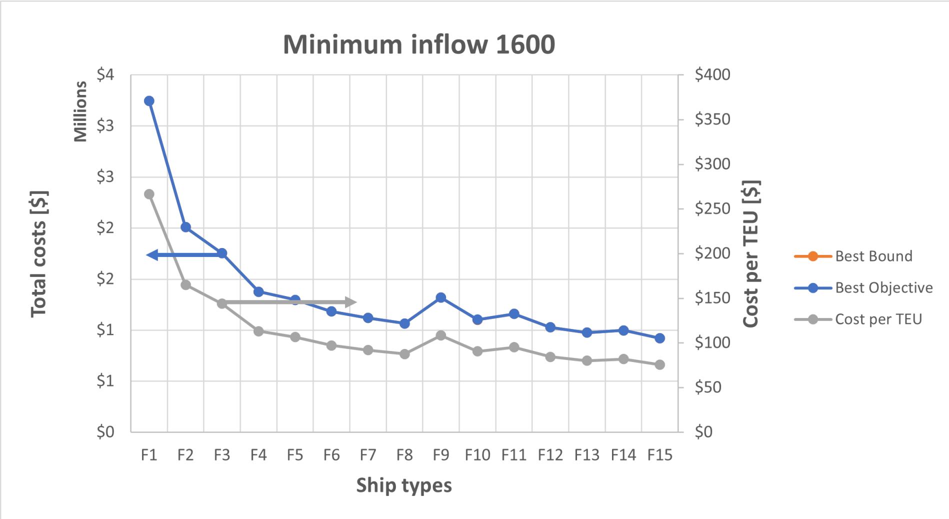

Figure C.21: Total cost [$] for container flows to ports with a minimum inflow of 1600 TEU per ship type for bunker costs of $500 per tonne

Table C.5: Cost per TEU [$] for ports with a minimum inflow [TEU] per ship type.

	Minimal inflow [TEU]								
Ship types	0	200	400	600	800	1000	1200	1400	1600
f1	$247.66	$247.66	$246.77	$248.06	$246.69	$247.87	$244.81	$247.04	$266.72
f2	$157.75	$152.23	$153.64	$153.88	$154.53	$154.95	$152.24	$153.78	$165.15
f3	$137.65	$131.19	$131.45	$132.25	$131.69	$132.37	$129.78	$132.79	$144.10
f4	$112.02	$105.99	$104.59	$104.79	$105.45	$105.03	$103.54	$105.10	$113.23
f5	$105.76	$99.11	$97.16	$96.15	$96.59	$96.77	$94.37	$97.02	$106.64
f6	$100.69	$93.34	$92.10	$90.26	$93.09	$92.08	$88.77	$90.64	$97.27
f7	$96.02	$87.60	$86.13	$85.38	$86.27	$86.88	$83.24	$85.17	$92.01
f8	$96.09	$86.41	$83.14	$82.99	$82.73	$84.12	$83.66	$83.28	$87.64
f9	$113.77	$101.39	$97.90	$95.94	$96.82	$96.03	$95.71	$100.47	$108.44
f10	$106.24	$94.52	$90.07	$87.90	$88.50	$87.90	$87.45	$86.61	$90.76
f11	$105.83	$92.20	$87.33	$84.17	$84.45	$84.93	$81.03	$84.97	$95.33
f12	$103.50	$88.67	$82.81	$79.55	$80.80	$80.76	$79.42	$79.36	$84.49
f13	$104.35	$88.47	$82.53	$79.48	$79.64	$80.48	$81.39	$80.82	$80.20
f14	$116.38	$90.30	$81.06	$77.23	$73.05	$73.62	$68.31	$69.38	$82.02
f15	$121.02	$91.62	$82.93	$74.73	$73.07	$73.74	$70.89	$74.76	$75.83