Erasmus University Rotterdam

Master Thesis

Operations Research & Quantitative Logistics

How will demand fluctuations, fleet composition, and bunker prices affect deep sea call sizes in Rotterdam?

Europe Container Terminals

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Abstract

For a container terminal operator it is of great importance to examine the call size development, since potentially larger call sizes caused by the use of ultra large container vessels (ULCS) put increasing pressure on terminals. Next to that, we expect the use of ULCSs to influence vessel routing and the number of port calls, which in turn indirectly affects the terminal. In order to determine the call size in Rotterdam, we come up with a mixed integer programming formulation which determines the container flow on the network and ship type that minimises total cost, given the demand volumes to the destinations, available fleet, and some routing scenario. The proposed model is able to solve the problem for each scenario within a negligible amount of running time for our problem instance. We observe that fluctuations in bunker prices do not affect routing choices and therefore the call size in Rotterdam at all, while using an ULCS or increasing demand such that an ULCS is needed, affect the routing choice and call size in Rotterdam in case Hamburg is called in the routing without a double call. When Hamburg is not used in the rotation, or a double call in Rotterdam is used, a large demand volume or the use of an ULCS do not affect routing choices or the call size in Rotterdam. We also observe that calling many ports in one rotation is not beneficial in terms of total costs. While executing this research, we discovered that fixed costs such as port call cost, ship operating cost, and fuel cost have a small influence on total costs, and are not likely to affect routing choices and therefore call sizes for our problem instance. On the contrary, costs incurred per TEU such as rail cost, terminal handling cost, and transshipment cost have a significant effect on routing choice. These insights in cost structure are very meaningful for a container terminal operator and can be used to improve its competitive position.

Contents

1 Introduction

The existance of ultra large container vessels (also referred to as ULCS) is a result of the growth in international container trade, which increased from 102 millions of tons loaded in 1980 to 1.631 millions of tons in 2014 (UNCTAD, 2015). The handling of these larger container vessels puts increasing pressure on terminals, as other facilities, e.g. larger cranes and more quay space, are required. With the ever growing vessel capacity, one would expect the call size (number of containers (un)loaded per call) to be increasing as well. In practice, however, this does not seem to be the case, as call size growth stays behind on vessel capacity development. It is of great importance to examine the call size development, as larger call sizes potentially provide high peaks in container stacking and hinterland transportation.

Besides the implications for terminals, we expect the use of ULCSs to affect vessel routing and the number of port calls, which in turn indirectly affects the terminal. Larger container vessels are well known to benefit from economies of scale at sea, but there may be disadvantages in ports (Mulder and Dekker, 2016b). Not all ports are capable of handling such large vessels, because of draft requirements and crane reach. A heavy loaded ULCS for example can not reach the port of Hamburg at low tide, since the Elbe is too shallow. To overcome this problem, vessels make 'double calls', i.e., some containers are discharged at Rotterdam before heading to Hamburg, and are loaded again after visiting Hamburg. This is very expensive in terms of the number of moves and port calls, and benefits from simultaneous loading and discharging are vanished. Next to that, port authorities charge higher costs for larger vessels, so making extra port calls will turn out to be very expensive. Therefore it would be interesting to investigate several vessel routing options and associated costs from a carriers point of view. In this way, we are able to obtain insight in different routing options upon which a carrier has to decide. In practice, we observe some unexpected behaviour from carriers regarding network design, as routing decisions are often based on agreements with companies and national interests, e.g. their behaviour is motivated by other reasons than economical routes. For example, in some cases shippers for German destinations automatically book through German ports, leaving carriers no alternatives. Besides that, shipping lines may have preferences for calling ports in their home country. For instance, Maersk is the only shipper that includes Aarhus in their Asia-Europe services at the moment. With this information in mind, it would be interesting to look at network design in a rational way, without considering interests and agreements that a liner shipper may have. This will provide insight in routing and port choice decisions a liner has to make, which is of great importance for a container terminal. In this way, a terminal is able to participate in due time to changes in port calls and call sizes in their terminal.

Network decisions that liner shippers face are nowadays further complicated by a market that is heavily subjected to change. At the moment, almost all shipping companies operate in alliances to improve performance. Sea-Land and Maersk began sharing ships in the Atlantic and Pacific oceans in 1990 (Agarwal and Ergun, 2010), and in the mid 1990s roughly 60% of the total global liner capacity was accounted by alliances. Nowadays alliance formation is still a common phenomenon among liner shipping operators. Carriers form strategic alliances by pooling their fleets and operating them together to share capacity on the vessels. In this way, carriers are able to offer higher sailing frequencies than would be possible using just their own fleet. Alterations in alliance formation can lead to substantial changes in container flows to a terminal, since contracts between shipping operators and terminals will be modified or even completely terminated. Another important issue in the current liner shipping market is overcapacity, which is strongly related to demand fluctuations and fleet composition. Due to the ever increasing vessel sizes, fleet composition changed significantly over the past years. Smaller vessels were scrapped and have been replaced by ULCSs. As demand growth did not keep up with the increase in vessel capacity, overcapacity was created. Overcapacity makes it difficult to control freight rates, which in turn influence shipping operators revenues (Midoro et al., 2005). Overcapacity may lead to changes in network structure, as operators prefer to avoid idle vessels. For example, vessels can be assigned to longer routes such that more vessels are required to maintain the same sailing frequency. This option is often combined with sailing below design speed (slow steaming), which can result in enormous operational costs savings due to the reduction in fuel consumption. However, we will not consider slow steaming, since it is beyond the scope of this research.

A last important factor on network structure and container flows is bunker price. Since bunker prices dropped enormously in the past years, fuel savings per container obtained by using ULCSs instead of conventional vessels, are vanished. When bunker prices decrease, we expect deep sea rotations to become longer, as the bunker cost of using a deep sea vessel will be relatively smaller. On the other side, we foresee deep sea rotations to become shorter in case of a higher bunker price. Next to that, differentiation in bunker price between ports may lead to changes in route networks. If bunker prices at a certain port are relatively low compared to neighbouring ports, it will be more attractive for a shipping operator to berth at that port, since operational costs consist for a major part of fuel costs (Stopford, 2009). This problem, however, lies beyond the scope of our research.

The major part of existing literature on liner shipping network design focuses on port-to-port connection and neglect hinterland destinations. However, for determining the container throughput in a port, it is of great importance to include hinterland transport in the model. Because of increased competition between ports, maritime carriers, and rail operators, exporters and importers (shippers) have access to more port and routing options (Drewry, 2016). Shippers aim for a route that has the best mix of costs, transit time and resilience. Drewry (2016) compared routes from the Northern Gate (Antwerp, Rotterdam, Hamburg) and Southern Gate (Genoa, Venice, Trieste, Koper, Rijeka, La Spezia, and Ravenna) to several hinterland locations in South Germany, in terms of transportation cost (maritime and rail), transit time, and frequency of rail departures. For most destinations, routing via Rotterdam may not be the fastest, but often it is the most beneficial option in terms of costs per container. Investigating the best route option for several demand destinations simultaneously will be a very interesting extension of Drewry's research.

With this knowledge in mind, we come up with the following research questions:

> *"How will fluctuations in demand volume and bunker prices affect the call size and container throughput in the port of Rotterdam?"*
>
> *"Will the use of ultra large container vessels lead to an increase in call sizes?"*

To answer the research questions, we come up with a mixed integer programming formulation which determines the container flow on the network and ship type that minimises total cost, given the demand volumes to the destinations, available fleet, and some routing scenario.

The thesis is structured as follows. First some information about the company this research is performed for is given. Secondly we will discuss the existing literature on liner shipping network design. After that, an extensive description of the problem is presented, together with the data that will be used. Next we will perform a preliminary analysis to get more insight into the problem and how different factors affect each other. Thereafter, we provide the overall solution approach that is going to be used in this thesis, and present the results obtained. Finally, a conclusion will be drawn and limitations of this research will be discussed.

1.1 Europe Container Terminals

This research is performed on behalf of Europe Container Terminals (ECT), a container terminal operator based in Rotterdam. It is one of the leading and most advanced container terminal operators in Europe; it handles a vast majority of all the containers passing through the port of Rotterdam. In addition, ECT offers customers through European Gateway Services (EGS) an expanding network of inland terminals which function as extended gates of the deep-sea terminals in Rotterdam. In this concept, trains and barges ensure highly frequent, reliable and especially also sustainable connections.

ECT was founded in 1966 shortly after the very first call from a container ship in Europe at Rotterdam. From handling nearly 500,000 containers in 1975, ECT grew on to handle more than one million containers in 1983. In 1985, ECT expanded with the opening of the ECT Delta Terminal at the Maasvlakte, close to the North Sea. With the opening of the Delta/Sea-Land Terminal (now the Delta Dedicated North Terminal) at the Maasvlakte in 1993, ECT was the first terminal operator worldwide to use Automated Guided Vehicles (AGVs) to take care of transport between the quay and container stacks, and the use of Automated Stacking Cranes (ASCs), to create the first modern automated container terminal. ECT again employed automation when it opened the ECT Delta Dedicated East Terminal in 1996 and the ECT Delta Dedicated West Terminal in 2000. In early 2002, ECT became part of the Hutchison Port Holdings (HPH) Group. HPH, a subsidiary of the multinational conglomerate CK Hutchison Holdings Limited (CK Hutchison), is the world's leading port investor, developer and operator. With the opening in 2008 of the Euromax Terminal Rotterdam at the north-westerly corner of the Maasvlakte, ECT took yet another step forward in terminal automation. (ECT, 2016)

Currently, ECT operates two deep-sea terminals in the port of Rotterdam: the ECT Delta Terminal and Euromax Terminal Rotterdam. Both situated at the Maasvlakte, directly on the North Sea. The terminals are operational 24/7 throughout the entire year. With these two terminals, together with the City Terminal which closed in October 2015, ECT handled more than 7.4 million TEU in 2015. In addition, ECT operates several own inland terminals in the European hinterland: MCT Moerdijk, TCT Venlo, DeCeTe Duisburg and TCT Belgium (Willebroek). Highly frequent rail and barge connections sustainably connect these inland terminals with ECT's deep-sea terminals, thus creating

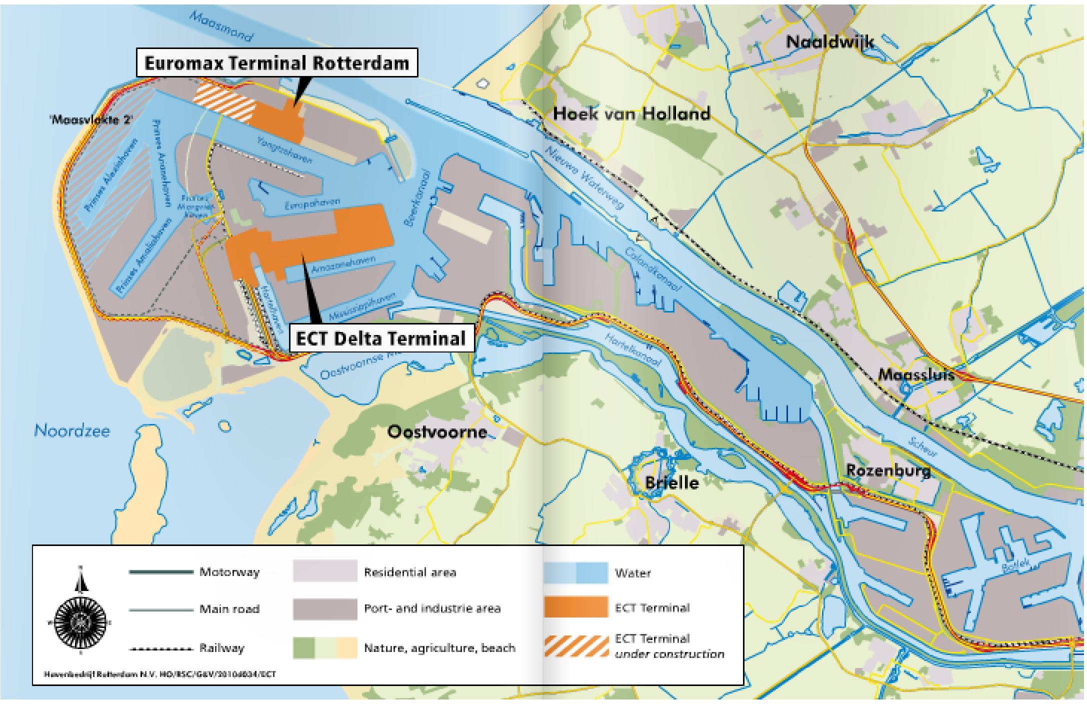

Figure 1: *Overview of ECTs terminals at the Maasvlakte*

an optimum logistics chain for customers. Naturally, all the inland terminals are also part of the larger inland network of European Gateway Services. (ECT, 2016)

Investigating the development of deep sea call sizes and container throughput is of great importance for ECT, since alterations in call sizes have a significant impact on terminal operations. For example, workforce planning, crane planning, and hinterland transportation are affected by changes in call sizes and throughput. By executing this research, ECT will be able to anticipate in due time to future market situations and corresponding call sizes and container throughput.

2 Literature review

In this section we will review existing literature related to our research, and discuss the research's contribution to the existing literature.

Container liner shipping operators need to decide about a wide variety of decision problems in operating a network. These decision problems can be divided into three planning levels. First, at the strategic planning level, operators decide on the fleet composition and which trade route to serve. Second, at the tactical planning level, the liner network needs to be designed, and the fleet deployment problem is solved. Finally, at the operational level, operators need to determine the cargo allocation on the network designed at the second planning level (Mulder and Dekker, 2016a). Existing literature regarding these problems can be divided into researches in which either one or multiple planning levels are addressed simultaneously. For example, the cargo routing problem and fleet deployment problem are often included in the network design problem. As our research mainly focuses on the second and third planning level, we do not review literature on fleet composition and trade choice.

Quite some articles on liner shipping network design can be found in the existing literature. Since 1983, about every 10 years, an overview of the existing literature on ship scheduling is given by Ronen (1983), Ronen (1993), Christiansen et al. (2004) and Meng et al. (2014).

As the liner shipping network design problem (LSNDP) can be reduced to a traveling salesman problem (TSP), it is NP-hard. Therefore, the methods proposed to solve the problem are mainly heuristics based on integer programming and decomposition techniques. The simultaneous scheduling and cargo routing problem is proven to be NP-complete by Agarwal and Ergun (2008). Often, smaller instances of the LSNDP can be solved to optimality using for example a MIP formulation or a branch-and-cut method as presented in Reinhardt and Pisinger (2012). The authors present a method that is among the first to include transshipment cost, and use a branch-and-cut method for solving a network design problem with butterfly routes to optimality for small instances.

Brouer et al. (2014) provides benchmark data instances (LinerLib) and a mixed integer programming formulation for the network design problem. The purpose of the benchmark suite is to provide easy access to data sources of liner shipping for OR researchers. The authors present a column generation approach to generate butterfly and pendulum routes. Imai et al. (2009) addresses the design of liner shipping networks while taking container management issues like empty container repositioning into account. Two different service networks are examined; multi-port calling by conventional ship size and hub-and-spoke by mega-ship. They found the multi-port networks to be superior to the hub-and-spoke networks in most scenarios except for European shipping operators serving the Asia-Europe trade lane. The researchers used different cost structures and ship types for the two different network types. In Mulder and Dekker (2016b) it is showed that even with the same cost structures and ship types, hub-and-spoke networks can be more profitable than multi-port networks. Gelareh et al. (2010) propose a mixed-integer programming formulation for hub-and-spoke network design in a competitive environment, where the competition between a newcomer liner service provider and an existing dominating operator is addressed. Next to that, a Lagrangian method combined with a primal heuristic were developed. A mixed-integer formulation is also used by Gelareh and Pisinger (2011) for the simultaneous design of a hub-and-spoke network and fleet deployment. A Benders decomposition-based algorithm was developed that outperformed general-purpose MILP-solvers. Gelareh et al. (2013) and Zheng et al. (2015) also use mixed-integer programming formulations to model the simultaneous hub location, feeder port allocation, fleet deployment and network design problem. Gelareh et al. (2013) proposes a Lagrangian decomposition approach since none of the existing general-purpose MIP solvers is able to solve even very small problem instances in a reasonable timespan. Zheng et al. (2015) uses a genetic algorithm embedded with a multi-stage decomposition approach to solve the model. Hsu and Hsieh (2007) formulate a two-objective model to determine the optimal liner routing, ship size, and sailing frequency for container carriers by minimizing shipping costs and inventory costs. Pareto optimal solutions of the two-objective model are determined and the routing decision on whether to route containers through a hub or directly to their destination can be made in objective value space. The optimal routing decision tends to be shipping the cargo through a hub. Wang and Meng

(2014) present a column-generation heuristic approach to find the best liner network, where each port can be visited on both the inbound and outbound direction. Plum et al. (2014) extend the butterfly routes used in Brouer et al. (2014) with multiple butterfly ports, hence their model allows recurrent calls of a service to a port, which previously could not be handled by LSNDP models.

Liu et al. (2014) presents an analysis for the network design problem of the intermodal liner shipping system. Existing methods for liner shipping network design mainly deal with port-to-port demand, but Liu et al. (2014) combine it with inland transportation. The authors start with an initial liner shipping network and try to improve it while also including transportation between ports and inland originations and destinations. The interaction between inland and maritime transportation lies in the choice of load (export) port and discharge (import) port as well as the origin–destination transit time considerations. In this thesis, we will also combine maritime transportation with inland transportation, but we will construct a combined network from scratch instead of improving an existing shipping network while adding an inland transportation network.

Transit time is an important factor to include in liner shipping network design. Wang and Meng (2011) evaluate the schedule design together with container routing for a fixed network to minimize transshipment cost and transit time. Notteboom (2006) assesses the trade-offs linked to the time factor in liner service schedules from the perspective of a shipping line. Notteboom concludes the number of port calls is decisive for the transit time at the end points of a liner service. Gelareh et al. (2010) support transit times and level of service as important factors in liner shipping network design. Karsten et al. (2015) studies the multi-commodity network flow problem with transit time constraints which puts limits on the duration of the transit of the commodities through the network. Their findings show that including transit time constraints does not increase the solution time and is essential to offer customers a competitive product. Instead of adding transit time constraints to the existing model, we will express transit time in terms of costs, and add this to our total cost function. In this way, we are able to put a soft constraint rather than hard constraint on transit time, which is desirable since transit time may not be the most important factor for a liner shipping company.

Our research contributes to the existing literature by including inland transportation. To our best knowledge, besides Liu et al. (2014) no other literature on liner shipping network design considers inland destinations. The literature on container ship routing and scheduling in liner shipping focuses mainly on the ocean side. Although there are quite a few studies on the inland transportation of containers, little research has been directed at the optimization of both inland and maritime transportation systems. (Meng et al., 2012). Next to that, we will consider the effects of fluctuating bunker prices, which is the dominant cost in operating a liner shipping network Stopford (2009). Finally, we include transit time in our model, which is proven to be an important factor in liner shipping network design.

3 Problem description

The main problem of this research is to determine the call size in the port of Rotterdam. Underlying problems are to decide on the least expensive cargo routing for a container and at which port to unload or transship a container. In order to give insight in the call sizes in the port of Rotterdam, we need to determine the container throughput in this port. We do this by considering several routing scenarios and their costs and transit times from a carriers point of view. Assuming a certain objective, in this research minimising total costs, we get insight in which ports are likely to be called for different inland destinations. Doing this for several inland and transshipment destinations, we are able to obtain better insights in container throughput of a certain port.

3.1 Assumptions

3.1.1 Markets and ports

As ultra large container ships are mainly used on the Asia-Europe trade lane, we choose to examine routing options only for this trade lane. Since we want to study network design in Northern Europe and Rotterdam in specific, all ports located east of the Suez canal will be aggregated into one demand and supply point, i.e. will be considered as one port. For convenience, we take Shanghai as a reference port to calculate distances and transit times. Furthermore, for the local market, we will only consider a selection of North Sea ports in the Hamburg-Le Havre range, as these ports are the main competitors of Rotterdam. Smaller ports like Zeebrugge and Eemshaven are left out of consideration, since their throughput and market share is relatively small. We also do not take Le Havre into account, since this port is mostly a competitor of Antwerp, and not so much of Rotterdam. Next to that, we assign a 'dummy node', which represents the remaining regions we do not consider in our model. In this way, we attempt to capture as much of the total market in our model as possible. In some scenarios we also include Gdynia as a deep sea port. Concluding, we consider the ports of Antwerp, Rotterdam, Bremerhaven, Hamburg, and Gdynia for the local market. We will refer to these ports as local ports. As local inland destinations, we consider the regions of Munich, Duisburg, Stuttgart, Vienna, Rotterdam/Antwerp area (RAA), and Hamburg/Bremerhaven area (HBA). The last two destinations represent local demand around Antwerp and Rotterdam, and Bremerhaven and Hamburg.

For the transshipment market, we will consider three regions; the Baltic, Scandinavia, and the UK, which are served by one of the local deep sea ports. To be precise, we consider the following three feeder loops:

– Loop 1: St. Petersburg - Gdynia

– Loop 2: Aarhus - Gotenborg - Kristiansand

– Loop 3: Southampton - Felixstowe

We do not consider feeder services to the Mediterranean, since this market is becoming very small.

3.1.2 Other assumptions

For this research, we assume carrier haulage, as this best reflects the choices a carrier would make. A carrier can be defined as a person, business, or organisation that offers transportation services via the sea on a worldwide basis (Agarwal and Ergun, 2008). In case of carrier haulage, the carrier also organises hinterland transportation. Next to that, we only consider import of containers, and neglect export. Hence, we only charge one-way costs; i.e. from Asia to Europe, and from a North Sea port to transshipment regions. We do not consider costs from Europe to Asia or from transshipment regions back to North Sea ports.

3.2 Scenarios

For a given set of inland destinations and corresponding demand, several routing scenarios are possible. A (routing) scenario refers to a vessel rotation. The exact vessel type is not captured in a scenario, only the vessel category is specified (i.e. deep sea and/or feeder). Each scenario consists of a set of nodes and arcs, where nodes correspond to ports, and where arcs connect these ports. To be precise, the origin node, or source node, refers to the port of Shanghai in our model. The dummy node is always the last node in a scenario, and represents regions we left out of consideration in our model. Distance to the dummy node is the same for each local port, such that a fair cost comparison can be made between different scenarios. In Figure 2 an example scenario is displayed. In this scenario, a deep sea vessel sails from Shanghai to Hamburg, from Hamburg to Rotterdam, and from Rotterdam to the dummy node. The dummy node is not displayed, as this is a symbolic node. Using this scenario, we need to determine the container flow to all demand destinations. Hinterland destinations will be served by train from Rotterdam and/or Hamburg, and transshipment regions are served by feeder from Rotterdam and/or Hamburg. For the transshipment market, we do not consider inland destinations since this will have little influence on which local port will be chosen. For example, for a certain inland destination in Sweden, calling either Gotenburg or Stockholm will most likely not influence the choice of local port. Feasibility of a scenario is determined by vessel capacity and terminal restrictions, e.g. a scenario where Hamburg is called with a 19k TEU vessel will not be feasible, due to tidal restrictions. Exceptions will be made for scenarios containing a double call.

We will consider the following scenario's in our research, where a standard arrow represents a deep sea service, and a feeder arrow represents a feeder service between two ports. These scenarios are combined with the transshipment loops described in Section 3.1.1.

- RH-scenario: SHA $\rightarrow$ RTM $\rightarrow$ HAM $\rightarrow$ DUM;
- HR-scenario: SHA $\rightarrow$ HAM $\rightarrow$ RTM $\rightarrow$ DUM;
- ARBH-scenario: SHA $\rightarrow$ ANR $\rightarrow$ RTM $\rightarrow$ BRV $\rightarrow$ HAM $\rightarrow$ DUM;
- ARBHG-scenario: SHA $\rightarrow$ ANR $\rightarrow$ RTM $\rightarrow$ BRV $\rightarrow$ HAM $\rightarrow$ GDY $\rightarrow$ DUM;
- RHR-scenario: SHA $\rightarrow$ RTM $\rightarrow$ HAM $\rightarrow$ RTM $\rightarrow$ DUM;
- RHfeeder-scenario: SHA $\rightarrow$ RTM $\rightarrow$ DUM; RTM $\xrightarrow{FEEDER}$ HAM;

The choice of scenarios is based on (parts of) existing shipping rotations in today's market. Scenarios with feeder services to Hamburg (RHfeeder-scenario) are at the moment not present in reality, but are likely to arise in the near future. Next to that, the port of Gdynia is not used in deep sea rotations at the moment, but due to terminal expansions we expect this to change.

Figure 2: *Example of a scenario*

3.2.1 Attributes

Our problem can be decomposed into the variables and parameters shown in Table 1. Given the demand volumes to the destinations, available fleet, and some routing scenario, we aim to find the container flow on the network and ship type that minimises total cost.

Variables	Parameters
Container flow	Volume demand destinations in TEU
Ship type(s)	Available fleet
	Routing scenario

Table 1: *Variables and parameters*

In order to find the best feasible container flow and ship type, we do not only consider total costs as a criterion, but also transit time. To capture transit time in our model, we express time in costs. Hence, the transit time costs can be added to the total scenario costs.

We define the total cost function of route m as follows:

$$C_m = FOC_m + PCC_m + THC_m + TSC_m + FC_m + RC_m + TTC_m \quad (1)$$

where FOC_m are fixed operating costs, PCC_m port call costs, THC_m terminal handling costs, TSC_m transshipment costs, FC_m fuel costs, RC_m rail costs, and TTC_m transit time expressed in costs of route m.

- Fixed operating costs FOC_m consist of charter cost, manning, insurance, stores/lubes, research, maintenance, and admin (Drewry), and are dependent on vessel type and sailing time.

- Port call costs PCC_m include harbour dues, pilotage, rowing, tugs, and possible quay charges. These costs are dependent on vessel type and port of call. In case of a double call in Rotterdam, a rebate of 75% on port call costs for the second call is applied.

- Terminal handling costs THC_m are terminal handling costs per TEU multiplied by the volume, and only depend on the port of call, not on vessel type.

- Transshipment costs TSC_m are the cost of transshipping one TEU multiplied by the volume. Transshipment takes place when a container is transshipped from one mode of maritime transport to another, e.g. from deep sea to feeder. For transshipment, no terminal handling costs are charged. In case of a transferral from maritime transport to inland transport, normal terminal handling costs are applicable. Transshipment costs are dependent on the port of call, not on vessel type.

- Bunker costs FC_m consist of the fuel consumption costs for maritime transportation modes. Fuel consumption in ton per day at a certain sailing speed is estimated by the following cubic function:

  $F(s) = (\frac{s}{v_*})^3 \cdot f_*$

  for sailing speed s, design speed v_*, and fuel consumption in ton per day at design speed f_*. Bunker costs depend on vessel type, sailing distance, and bunker price. For the sake of simplicity, we assume the sailing speed to be equal to the design speed of a vessel.

- Rail costs RC_m consist of rail costs to transport a certain volume from port to inland destination. Inland transport costs depend on distance covered and the number of TEU transported.

- Transit time cost TTC_m is the transit time of route m expressed in capital. Transit times are determined from origin to destination, and include port time. We assume port time to be larger for deep sea vessels than for feeders. As transit time may not be the most important factor for a carrier, we only include 10% of the transit time costs in the total cost calculations.

3.3 Data

In order to determine the route costs and transit times explained in Section 3.2.1 we need data to obtain realistic values for these attributes. Data is retrieved from the following sources:

- (1): ECT
- (2): LinerLib dataset from Brouer et al. (2014)
- (3): Drewry Maritime Research
- (4): European Gateway Services (EGS)
- (5): Port of Rotterdam

As not all data we need is available, we fill unknown data points by extending known data in a linear way or by estimation. These data points are marked by an asterisk (*). A list of port and destination abbreviations can be found in Table 33 in the Appendix.

The following information is needed:

- Vessel characteristics (Table 2 & Table 3): capacity, charter cost, operating cost(including charter cost), design speed, and fuel consumption at design speed. In Table 4 the daily operating costs (without charter cost) are also given per TEU, for fully (100%) and 80% loaded vessels. We note that operating cost per TEU of vessel 4 are not in line with the decreasing pattern that can be observed when vessel size increases. This can be caused by the estimation of operating and charter costs of vessel 4. In Table 35 in the Appendix, the names corresponding to the vessels used in this research are given.

- Terminal handling cost and transshipment cost per TEU (Table 5). Terminal handling costs are charged if a container enters the terminal at seaside and leaves the terminal at landside, i.e. it will be transported to its inland destination by train. Transshipment costs are in incurred when a container is transshipped from some maritime transportation mode to another, e.g. from deep sea to feeder. Terminal handling costs that a carrier charges to its client are provided by the Port of Rotterdam(5) and ECT(1) and are publicly available. However, we would like to obtain the costs that a terminal charges to the carrier, which are confidential, and therefore not provided. We estimate these costs by taking 75% of the publicly available costs.

  Transshipment costs are obtained by LinerLib(2). As these costs are given per FFE (forty foot equivalent), we need to scale down the costs since the number of moves is slightly higher. Therefore, we divide the costs by 2 and multiply by 1.7 (TEU factor) to obtain the transshipment costs per move.

  Terminal handling and transshipment costs given in this section are the best possible estimates, but should not be interpreted directly, since transshipment costs are perturbed by LinerLib, and terminal handling costs are estimated by taking 75% of the publicly available costs. Therefore, no conclusions about competitiveness should be drawn.

- Port call costs (Table 6) are charged when entering a port. Port call costs are given for every ship type and local port (Hamburg, Bremerhaven, Rotterdam, Antwerp, Gdynia), and are provided by ECT in cooperation with the Port of Rotterdam. For ports in transshipment regions, we set port call costs to zero. This is permissible since these ports are always called in every solution, and can only be visited by one ship type (feeder), so port call costs of these ports are constant in every solution. If Gdynia is used as a deep sea port, we set its port call costs, terminal handling cost, and transshipment cost equal to that of Bremerhaven (marked by **). For ship type 1, no port call costs are known for Bremerhaven. Therefore we set these costs equal to the port call costs in Hamburg for ship type 1. We observe that sometimes port call costs are lower for a smaller ship, e.g. type 4 is cheaper than type 3 in Rotterdam. Next to that, if some port is cheaper than some other port for a given ship type, it does not mean it is cheaper for all ship types, e.g. Antwerp has lower port call costs than Hamburg for ship types 2 and 3, but for other ship types, calling Antwerp is more expensive. This can be due to discounts that are given to some ship types in certain ports, or different vessel drafts. Each port determines port call costs in various ways, hence the data given may be somewhat inconsistent.

- Distance between two ports, retrieved from LinerLib (Table 32, Appendix). Distance to the dummy node is set to 200 mile for every port except Shanghai. For calculating the distance from Shanghai to the dummy node, we use the same distance as from Shanghai to Felixstowe. In this way, the dummy node will not influence results, as costs will be the same for sailing from every port preceding the dummy node to the dummy node itself.

- Demand to hinterland and transshipment destinations (Table 7), retrieved from both Drewry and Linerlib. For demand at hinterland destinations, we use population data from Drewry (Drewry, 2016) to obtain demand per region, as LinerLib only provides port-to-port demand. Demand at transshipment destinations is retrieved from LinerLib. Thereafter, we scale the data such that demand is distributed as follows; 40% of the demand represents the inland market, 20% the transshipment market, and 40% the remaining market which is represented by the dummy node. Scaling of the demand data is necessary since demand volumes are obtained from multiple sources, and therefore demand between different markets was not in proportion. Next to that, we scale down total demand volume such that it can be carried on one deep sea vessel.

- Bunker price; for sailing from Asia to the Mediterranean we use IFO 380, which costs €200 per metric ton (08/09/2016, http://shipandbunker.com/). Due to fuel regulations in the Baltic Sea area and the North Sea area; ships have to use fuel oil with a sulphur content of no more than 0.10% from 1 January 2015 (http://www.imo.org/). Therefore we set the bunker price to €400 (MGO)[(5)] for sailing in Northern Europe.

- Inland transport characteristics: rail costs and transit time from port to hinterland destination are given in Table 8 and Table 9. Rail tariffs are obtained from European Gateway Services and Drewry (Charlesworth, 2013). Values marked by an asterisks were not available from the used data, and are estimated based on distance. For rail

Ship	Type	Capacity in TEU	Charter cost[3] €/day	Operating cost[3] (incl. charter) €/day
1	Feeder	1.000	4.000*	5.013*
2	DS	8.110	11.000	17.704*
3	DS	13.102	14.500	25.349
4	DS	14.000	16.000*	27.503*
5	DS	16.000	17.000*	30.224*
6	DS	19.224	18.000*	34.017

Table 2: *Vessel characteristics part 1. Values marked with an asterisk (*) are obtained by estimation.*

Ship	Type	Design speed in knots[1]	Fuel consumption ton/day at design speed[2]
1	Feeder	14	24
2	DS	17	80
3	DS	17*	110*
4	DS	17*	127
5	DS	16*	150*
6	DS	16*	164*

Table 3: *Vessel characteristics part 2. Values marked with an asterisk (*) are obtained by estimation.*

costs to the Rotterdam/Antwerp-area and Hamburg/Bremerhaven-area we use a tariff of €0.50 per road kilometre. The same kilometre tariff is used to calculate rail costs from Gdynia to each hinterland destination. In reality, not all port-hinterland combinations will have a rail connection. However, the costs given will represent other hinterland transport modalities in case no rail connection is provided. Due to the various sources and estimation of unknown data points, the data contains inconsistencies. Hence, the data should not be interpreted directly, and no further conclusions should be drawn from the values used.

– Time in port, which is set to 1.5 days for deep sea vessels and 0.5 days for feeders.

– Port capacity restrictions; port capacity is bounded from above by 16.000 and 14.000 TEU for the ports of Hamburg and Gdynia, respectively (https://www.hafen-hamburg.de/). At the moment, Gdynia can handle deep sea vessels up to 10.000 TEU, but in 2017 this will be expanded to 14.000 TEU, which we will use in this research. In case of a double call we assume all vessels are able to enter the port of Hamburg, since the vessel is only partially loaded after its call at Rotterdam, and export containers leaving Rotterdam are loaded at the second call.

– Transit time cost; in Table 34 in the Appendix the value of containers for different cargo categories provided by ECT are exhibited. We take the average value of a 20ft container over all cargo categories. We assume a holding cost rate of 15% per year, and thus holding cost per day for a container worth €57.030 is €23,44.

Ship	Operating cost/day	Operating cost/day/TEU	Operating cost/day/TEU 80%
1	3.576	3,58	4,47
2	9.835	1,21	1,52
3	12.964	0,99	1,24
4	14.305	1,02	1,28
5	15.199	0,95	1,19
6	16.093	0,84	1,05

Table 4: Operating costs (excluding charter cost) per TEU for 100% and 80% occupation in €

	Rotterdam	Hamburg	Antwerp	Bremerhaven	Gdynia**
THC$^{(1)(5)}$	149	167	132	167	167
TSC$^{(2)}$	112	170	93	92	37

Table 5: *Terminal handling costs and transshipment costs per TEU in €, both obtained by estimation*

Type	Rotterdam	Hamburg	Antwerp	Bremerhaven	Gdynia**
1	8.446	8.406	10.668	8.406*	8.406
2	58.884	67.209	59.833	55.660	55.660
3	86.325	82.192	81.988	69.720	69.720
4	84.457	83.952	84.948	70.632	70.632
5	97.816	85.590	97.563	73.298	-
6	108.744	87.323	106.538	67.647	-

Table 6: *Port call costs for all vessel types in €*$^{(1)(5)}$

Node	Demand	Node	Demand
SHA	0	KRS	6
ANR	0	SOU	492
RTM	0	FXT	1.370
BRV	0	MUN	485
HAM	0	STU	1.034
DUM	6.250	DUI	1.211
STP	496	VIE	863
GDY	42	RAA	1.313
AAR	288	HBA	1.313
GOT	334	Total	15.497

Table 7: *Demand volume in TEU for every destination*

Cost	MUNCHEN	STUTTGART	DUISBURG	VIENNA	RAA	HBA
ANR	326	464*	258*	428	35*	243*
RTM	217	355	149	428	35*	233*
BRH	225	350*	170*	273	213*	35*
HAM	225	350*	170*	277	255*	35*
GDY	585*	608*	518*	468*	595*	403*

Table 8: *Rail cost per TEU in €. Values marked with an asterisk (*) are obtained by estimation, and non-marked values are obtained by multiple sources, which causes inconsistencies in the data.*

Days	MUNCHEN	STUTTGART	DUISBURG	VIENNA	RAA	HBA
ANR	2	2	2	2	1	1
RTM	1	1	1	3	1	1
BRH	1	1	1	2	1	1
HAM	1	1	1	2	1	1
GDY	2	2	2	2	2	1

Table 9: *Transit time of rail connections in days*

4 Preliminary analysis: Rotterdam - Munich

4.1 Introduction, assumptions, and data

We will perform a preliminary analysis on network design to get insight in the influence of several factors and how they affect each other. To do so, we examine a very small part of a network, for instance the service line between Rotterdam and Munich. We consider four possible scenarios for this demand location:

– Scenario 1: Sailing from Rotterdam to Hamburg with a deep sea vessel, and serve Munich by train from Hamburg.

– Scenario 2: Sailing from Rotterdam to Hamburg with a feeder, and serve Munich by train from Hamburg.

– Scenario 3: Do not sail to Hamburg at all, and serve Munich by train from Rotterdam.

– Scenario 4: Sailing from Rotterdam to Hamburg with a deep sea vessel, but serving Munich by train from Rotterdam.

We will compare total costs for these scenarios, and examine the effect of alterations in factors as demand and bunker price on total costs. Finally we will determine total cost break-even points to determine which scenario has the lowest total costs for varying demand and bunker prices.

4.2 Total cost comparison

In this section we will compare total costs between the scenarios, using the data described in Section 3.3. Furthermore, we use vessel type 5 (16.000 TEU) for this analysis, and assume a demand volume of 1200 TEU. In Figure 3 the cost per category is displayed graphically, and in Table 10 the exact costs are exhibited. These costs are calculated as explained in Section 3.2.1. We conclude that minimum costs with the current parameter settings are obtained by Scenario 3 and therefore sailing only to Rotterdam and serving Munich from Rotterdam by train is the least expensive option when only considering Munich as a demand destination. Sailing from Rotterdam to Hamburg and serving Munich from Hamburg by train turns out to be the most expensive routing option.

4.3 Sensitivity analysis

In this section we will examine the effects of alterations in demand volume and bunker price on the total costs. We vary these factors by 15%, and determine the percentage deviation in total costs. The costs given in Table 10 are used as a benchmark. The results are displayed in Table 11. Alterations in demand volume seem to have a larger impact on total costs than fluctuations in bunker prices. For example, if demand increases with 15%, total costs increase with 10.7% for scenario 1, while total costs only increase with 0.8% for this scenario when bunker prices increase by 15%. The effect of altering demand volumes and bunker prices is linear and thus the positive and negative effect is equal.

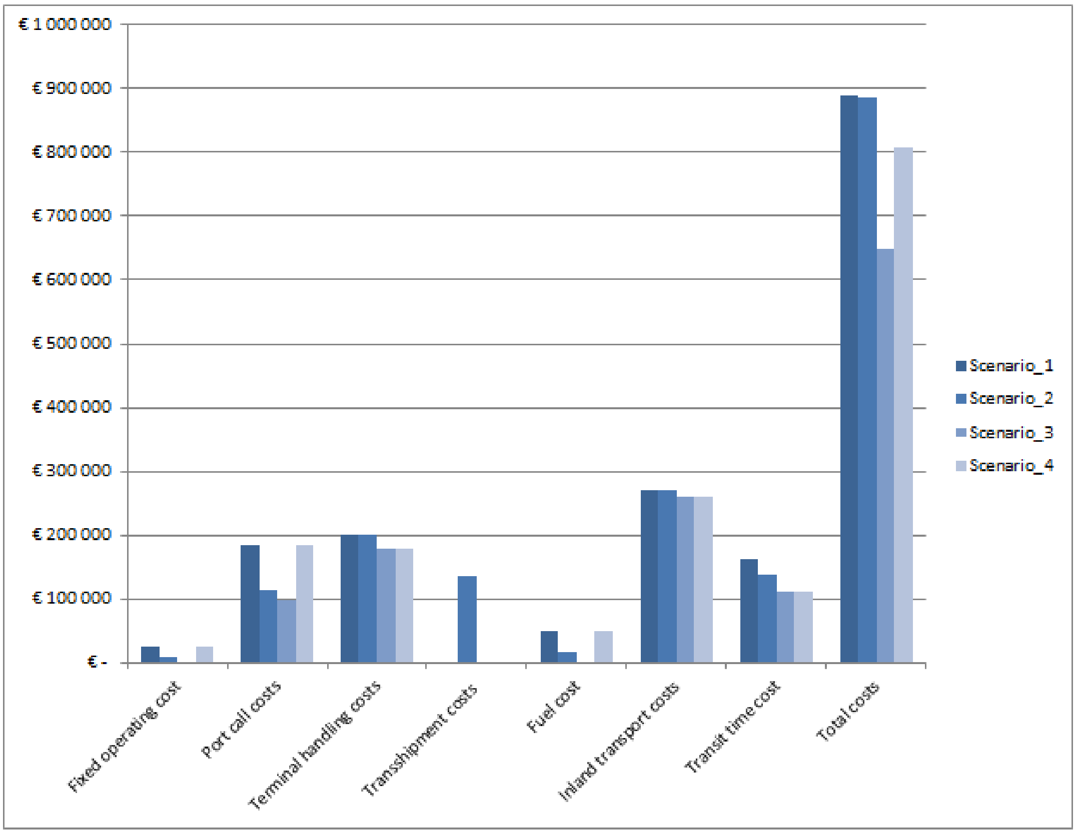

Figure 3: *Graphical display of cost structure (in €) for all scenarios*

	Scenario_1	Scenario_2	Scenario_3	Scenario_4
Fixed operating cost	24.164	9.161	0	24.164
Port call costs	183.406	114.628	97.816	183.406
Terminal handling costs	200.700	200.700	179.100	179.100
Transshipment costs	0	134.966	0	0
Fuel cost	47.969	17.324	0	47.969
Inland transport costs	270.000	270.000	260.400	260.400
Transit time cost	163.128	138.212	112.512	112.512
Total costs	889.366	884.991	649.828	807.551
Cost per container	758	747	551	690

Table 10: *Cost per category for all scenarios, in €*

Alterations in demand volume have the largest effect on scenario 3, while fluctuations in bunker prices have the largest effect on scenario 4.

Furthermore, we study the impact of inserting different vessel types in the model. From the results in Table 12 we see that using other vessel types has the largest effect on scenario 4. Percentage deviations are given between brackets, where using deep sea vessel 4 (14.000 TEU) serves as a benchmark.

Factor	(-)15% Demand volume			
Scenario	S1	S2	S3	S4
Deviation from total cost	(-)10.7%	(-)12.6%	(-)12.7%	(-)10.3%
Factor	(-)15% Bunker price			
Scenario	S1	S2	S3	S4
Deviation from total cost	(-)0.8%	(-)0.3%	(-)0.0%	(-)0.9%

Table 11: *Sensitivity analysis Rotterdam-Munich*

Ship type	S1	S2	S3	S4
2	795.997 (-7.4%)	846.059 (-2.9 %)	610.896 (-4%)	715.504 (-8.2%)
4	859.803	871.633	636.469	779.311
6	909.537 (5.8%)	895.919 (2.8%)	660.756 (3.8%)	827.721 (6.2%)

Table 12: *Total costs for using three different ship types, in €*

4.4 Break-even points

In this section we aim to find the total costs break-even points, i.e. where total costs for two scenarios are the same. First, we aim to find the demand where total costs are the same for two scenarios. This can be seen graphically in Figure 4. To be precise, the total costs of scenario 1 and scenario 2 coincide for a demand of 1348 TEU. Total costs of scenario 2 and scenario 4 coincide for a demand of 909 TEU. Finally, total costs of scenario 1 and scenario 4 coincide at a demand of zero. Jumps in the total cost function of scenario 2 are caused by the number of feeder vessels used, e.g. at a jump, an extra vessel is needed, which involves additional costs for operating another vessel. Concluding, scenario 3 is the least expensive routing option for all demand volumes, followed by scenario 4 for demand volumes larger than 909 TEU. For demand volumes larger than 1348 TEU, feedering from Rotterdam to Hamburg is the most expensive routing choice.

Secondly, we aim to find the break-even point for varying bunker prices. The total costs for all scenarios are displayed in Figure 5 for varying bunker prices. Total costs of scenario 1 and scenario 2 coincide for a bunker price of €245 per ton. Total costs of scenario 2 and scenario 4 coincide for a bunker price of €1177 per ton. Total costs of scenario 3 remain constant, since no vessel is used in this routing option, and thus no fuel costs are incurred. Since fuel consumption of a feeder is significantly lower than that of a deep sea vessel, total costs for scenario 2 increase less rapidly than total costs for scenario 1 and 4.

4.5 Conclusions

In this section we studied a small part of a network, namely Rotterdam - Munich. It turns out that transporting containers directly from Rotterdam to Munich by train, and thereby skipping Hamburg, is the cheapest option. Studying the influence of parameters, we can conclude that demand volume has a significant effect on total costs, while fluctuations in bunker price have a smaller effect and do not influence routing decisions for the carrier within the studied bandwidth. Demand alterations have the largest effect on scenario 3,

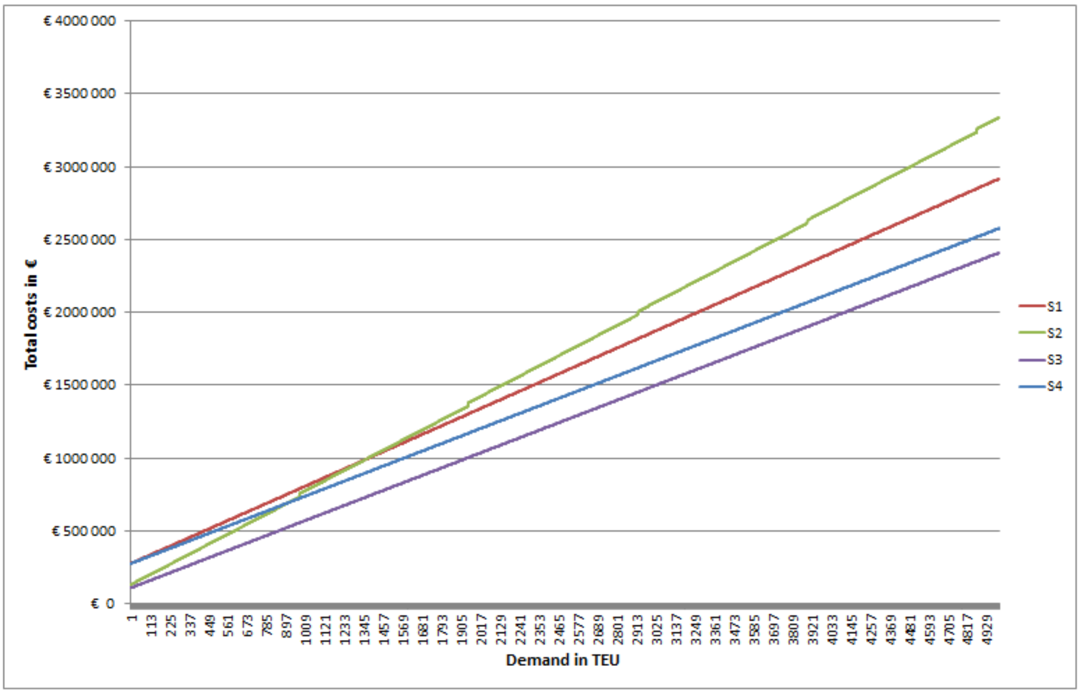

Figure 4: *Total costs break-even point for varying demand*

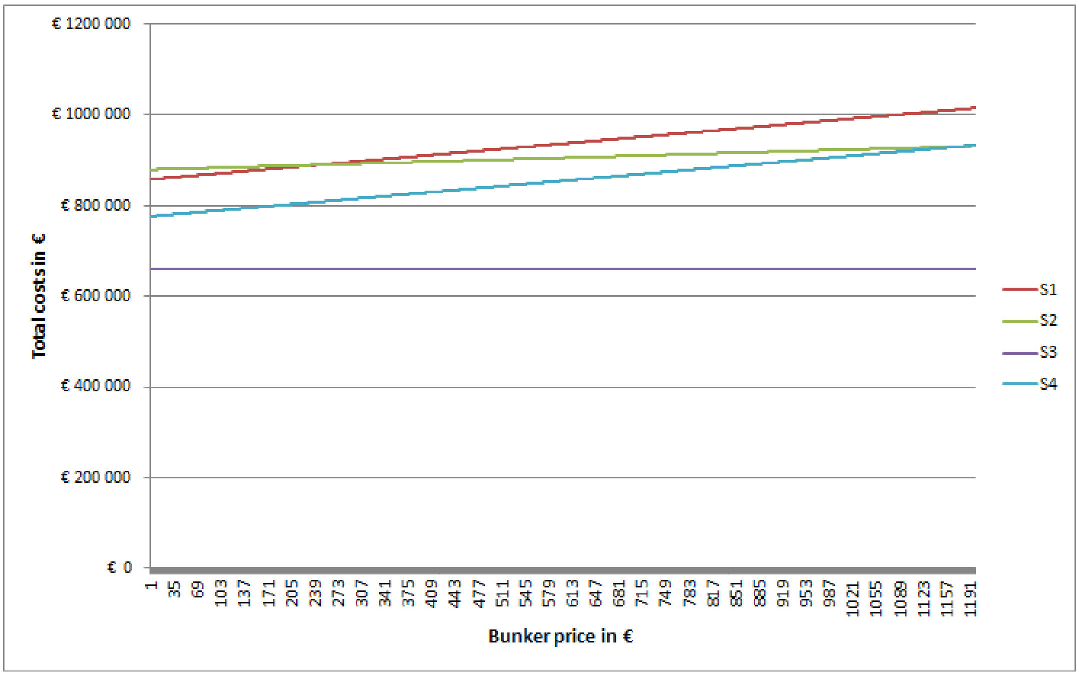

Figure 5: *Total costs break-even point for varying bunker prices*

as total costs consist for a major part of costs per TEU (e.g. rail cost) and fixed costs are quite lower since no vessels are used in this scenario. Bunker price fluctuations have the largest effect on scenario 4, since a deep sea vessel uses more fuel than a feeder vessel or no vessel at all. Changes in vessel type also influence scenario 4 the most, since in Scenarios 2 and 3 only port call cost change with the vessel type. The effect on vessel costs is the same for scenario 1, but since its total costs are higher, the impact of using another vessel type on total costs is lower. Scenario 3 is the least expensive routing option for all demand volumes, followed by scenario 4 for demand volumes larger than 909 TEU. For demand volumes larger than 1348 TEU, feedering from Rotterdam to Hamburg is the most expensive routing choice. Scenario 1 is the most expensive option for bunker prices higher than €245 per ton, and scenario 3 and 4 are the least costly routing choices for almost all bunker prices.

In this section, we determined the cheapest routing option for one demand destination, to obtain some first insights in cost structures and how parameters affect total costs. In the next section we will establish a method for our overall problem, that is, determining the cheapest routing option and container flow for several inland and transshipment destinations.

5 Overall solution approach

In this section, we will establish the overall solution approach for our problem. In the previous section, we only studied a small part of a network. With the method provided in this section, we will be able to examine a network consisting of several inland and transshipment destinations. Given a certain demand volume to a set of destinations and a certain routing scenario, we aim to find an optimal cargo allocation where total costs and transit time are minimised. For several routing scenarios, we want to solve the cargo allocation problem, where the optimal container flow on the routing scenario and vessel type(s) are determined.

5.1 Mathematical formulation

The problem can be formulated as a flow problem, where the nodes of the graph correspond to deep sea and transshipment ports and inland destinations. The arcs represent some transportation mode between nodes, i.e. deep sea vessel, feeder, or rail. The following sets, decision variables, and parameters are used:

Sets:

- N: set of all nodes;
- O: set of origin nodes, $O \subset N$;
- D: set of destination nodes, $D \subset N$;
- T: set of remaining nodes, $T \subset N$, $T \cup O \cup D = N$, and $T \cap O \cap D = \emptyset$;
- P: set of port nodes, $P \subset N$;
- PT: set of transshipment ports, $PT \subset P$;
- PL: set of local ports, $PL \subset P$, $PT \cup PL = P$, and $PT \cap PL = \emptyset$;
- H: set of hinterland destinations, $H \subset N$;

- C: set of vessel categories, C = {deep sea, feeder};
- V: set of vessels, consisting of deep sea and feeder vessels.

Decision variables:

- x_{ijs}: number of containers (in TEU) transported on arc $i \rightarrow j$ corresponding to vessel type s
- $y_{ijs} = \begin{cases} 1 & \text{if arc } x_{ijs} \text{ is used} \\ 0 & \text{otherwise} \end{cases}$
- $z_s^c = \begin{cases} 1 & \text{if vessel s from ship category c is used} \\ 0 & \text{otherwise} \end{cases}$

Parameters:

- $fixed_{ijs}$: fixed operating cost of arc $i \rightarrow j$ using ship type s;
- $fuel_{ijs}$: fuel cost of arc $i \rightarrow j$ using ship type s;
- pcc_{ijs}: port call cost of arc $i \rightarrow j$ using ship type s consists of the port call cost of port i;
- thc_{ij}: terminal handling cost per TEU at node i;
- tsc_{ij}: transshipment cost per TEU at node i;
- rc_{ij}: rail cost of inland arc $i \rightarrow j$;
- ttc_{ijs}: cost of transit time of arc $i \rightarrow j$ using ship type s;
- d_j: demand volume in TEU at destination j
- u_{ijs}: capacity of arc $i \rightarrow j$ using ship type s in TEU

The mathematical formulation becomes:

$$
\begin{aligned}
min \quad & \sum_{i\in N}\sum_{j\in N}\sum_{s\in V}[fixed_{ijs} + fuel_{ijs} + pcc_{ijs}]y_{ijs} + \\
& \sum_{i\in N}\sum_{j\in N}\sum_{s\in V}[rc_{ij} + ttc_{ijs}]x_{ijs} + \sum_{i\in N}\sum_{j\in H}\sum_{s\in V} thc_{ij}x_{ijs} + \sum_{i\in N}\sum_{j\in PT}\sum_{s\in V} tsc_{ijs}x_{ijs} && (2)\\
s.t. \quad & x_{ijs} \leq u_{ijs} \quad \forall i,j \in P, s \in V && (3)\\
& \sum_{j\in N}\sum_{s\in V}[x_{ijs} - x_{jis}] = \begin{cases} 0 & \text{if } i \in T \\ \sum_{j\in D} d_j & \text{if } i \in O \\ -d_i & \text{if } i \in D \end{cases} && (4)\\
& \sum_{i\in P}\sum_{j\in P} x_{ijs} \leq M z_s^c \quad \forall c \in C, s \in V && (5)\\
& \sum_{s\in V} z_s^c = 1 \quad \forall c \in C && (6)\\
& x_{ijs} \leq M y_{ijs} \quad \forall i,j \in N, s \in V && (7)\\
& \sum_{j\in PL} y_{ijs} \leq 1 \quad \forall i \in P, s \in V && (8)\\
& y_{ijs}, z_s^c \in \mathbb{B} \quad \forall i,j \in N, s \in V, c \in C && (9)\\
& x_{ijs} \in \mathbb{N}, \quad \forall i,j \in N, s \in V && (10)
\end{aligned}
$$

The objective function 2 minimises total cost of the container allocation on a chosen routing, consisting of fixed and variable costs. Constraints 3 make sure the container flow on an arc does not exceed the capacity of the vessel serving that arc. We assume rail arcs to have infinite capacity. Constraint set 4 reserves the container flow on the arcs, i.e. the number of container going into a node should be equal to the number of container going out of a node, except for the origin and destination nodes. Constraints 5 ensure no containers can be allocated to an arc if the vessel corresponding to that arc is not chosen. This must hold for both vessel categories, where category 1 corresponds to feeder vessels and category 2 to deep sea vessels. Next to that, we want at most one vessel to be chosen per category, which is captured in constraints 6. With constraints 7 we ensure y_{ijs} to be zero when no flow exists on arc $i \rightarrow j$ using vessel s, and one when the flow is positive. Constraints 8 make sure the deep sea vessel sails a roundtrip, i.e. only one port is directly visited after some other port. This does not hold for the transshipment market, since multiple transshipment destinations can be served from the same local port. Finally, we want to make sure y_{ijs} and z_s^c are binary, and x_{ijs} is integer, which is captured in constraints 9 and 10, respectively. Different scenario routings are imposed by changing the capacity matrix u_{ijs}. That is, u_{ijs} is equal to the capacity of vessel s if arc $i \rightarrow j$ is part of the routing scenario, and zero otherwise.

5.1.1 Calculation of port call costs

To correctly calculate the port call costs, we need some tricks. Port call costs are incurred when a vessel visits a local port, and when a feeder leaves a local port to serve some transshipment destination. The latter is straightforward and can be determined by:

$\sum_{i\in P}\sum_{j\in PT}\sum_{s\in V} pcc_{ijs} \cdot y_{ijs}$ However, to determine the port call costs at local ports, we need to perform some tricks. If we would calculate port call costs as above, port call costs are charged multiple times for the same port, as one port can serve multiple inland destinations. To overcome this problem, an auxiliary decision variable a_{is} is constructed, where a_{is} is 1 if local port i is visited by vessel s, and zero otherwise. These values are determined by the following constraints:

$$\sum_{j\in H} y_{ijs} \leq M a_{is} \quad \forall i \in PL, s \in V \tag{11}$$

$$a_{is} \leq \sum_{j\in H} y_{ijs} \quad \forall i \in PL, s \in V \tag{12}$$

Next we construct additional parameters $pcc2_{is}$ with port call costs for every port i and vessel type s. Port call costs of local ports are then determined by $\sum_{i\in PL}\sum_{s\in V} pcc2_{is} \cdot a_{is}$.

6 Results

In this section we will present the results obtained from our overall model. We start with the results of the six scenarios obtained with the data as given in Section 3.3, from now on referred to as the base case. Thereafter, we examine the effects of using a larger vessel type, and the effects of alterations in demand volume and bunker price on routing choice and container throughput in Rotterdam.

6.1 Results base case

In this section we provide the results of our model for the scenarios given in Section 3.2 with the data given in Section 3.3 as input data. For every scenario, the same deep sea vessel is chosen by the model in the optimal solution, namely type 5 (16.000 TEU). We will now provide the container flow and total costs as obtained in the optimal solution for every scenario. For example, in Table 13 the flow of the RH-scenario is given for deep sea, feeder and rail. The number above each arc represents the container flow on that arc. In Table 14 the total costs per container in the optimal solution are given in the first column, and the total costs for sailing the input rotation as indicated in Section 3.2 are given in the second column. When calculating the cost of sailing the input rotation, we assume the container flow to be the same as in the optimal solution. Hence, we calculate the additional costs of visiting ports that are skipped in the optimal solution. In some scenarios, total costs and total cost when sailing the input rotation are equal. Finally, a map with arcs used in the optimal solution is provided for each scenario. In these maps, deep sea arcs are represented by solid lines and feeder and rail arcs by dashed lines. The dummy node is not included in these figures to avoid a lack of clarity. The running time of our model is less than one second for each scenario.

RH-scenario	Flow
Deep sea	SHA $\xrightarrow{15497}$ RTM
	RTM $\xrightarrow{8426}$ HAM
	HAM $\xrightarrow{6250}$ DUM
Feeder	RTM $\xrightarrow{538}$ STP
	STP $\xrightarrow{42}$ GDY
	RTM $\xrightarrow{628}$ AAR
	AAR $\xrightarrow{340}$ GOT
	GOT $\xrightarrow{6}$ KRS
	RTM $\xrightarrow{1862}$ SOU
	SOU $\xrightarrow{1370}$ FXT
Rail	RTM $\xrightarrow{485}$ MUN
	RTM $\xrightarrow{1034}$ STU
	RTM $\xrightarrow{1211}$ DUI
	RTM $\xrightarrow{1313}$ RAA
	HAM $\xrightarrow{863}$ VIE
	HAM $\xrightarrow{1313}$ HBA

Table 13: Container flow RH-scenario

Rotation	Optimal	Input
Fixed cost	1.176.404	1.176.404
Fuel cost	1.316.181	1.316.181
Port call cost	214.614	214.614
Terminal handling cost	965.799	965.799
Transshipment cost	339.136	339.136
Rail cost	983.715	983.715
Transit time cost	1.409.878	1.409.878
Total cost	6.405.727	6.405.727
Cost per container	413	413

Table 14: Cost structure RH-scenario in €

We observe that in the optimal solution for the RH-scenario, all ports from the input rotation are used. All transshipment destinations are served from Rotterdam, since transshipment costs in Rotterdam are substantially lower than in Hamburg (€112 versus €170). The sailing distance from Hamburg to Sint Petersburg and Aarhus is shorter than from Rotterdam, but the savings in operating and fuel costs (€8.342) do not outweigh the extra transshipment costs (€67.628) when serving Scandinavia and the Baltic by Hamburg instead of Rotterdam.

Figure 6: Flow RH-scenario

HR-scenario	Flow
Deep sea	SHA $\xrightarrow{15497}$ HAM
	HAM $\xrightarrow{13321}$ RTM
	RTM $\xrightarrow{6250}$ DUM
Feeder	RTM $\xrightarrow{538}$ STP
	STP $\xrightarrow{42}$ GDY
	RTM $\xrightarrow{628}$ AAR
	AAR $\xrightarrow{340}$ GOT
	GOT $\xrightarrow{6}$ KRS
	RTM $\xrightarrow{1862}$ SOU
	SOU $\xrightarrow{1370}$ FXT
Rail	RTM $\xrightarrow{485}$ MUN
	RTM $\xrightarrow{1034}$ STU
	RTM $\xrightarrow{1211}$ DUI
	RTM $\xrightarrow{1313}$ RAA
	HAM $\xrightarrow{863}$ VIE
	HAM $\xrightarrow{1313}$ HBA

Table 15: Container flow HR-scenario

Rotation	Optimal	Input
Fixed cost	1.196.789	1.196.789
Fuel cost	1.356.852	1.356.852
Port call cost	214.614	214.614
Terminal handling cost	965.799	965.799
Transshipment cost	339.136	339.136
Rail cost	983.715	983.715
Transit time cost	1.460.762	1.460.762
Total cost	6.517.668	6.517.668
Cost per container	421	421

Table 16: Cost structure HR-scenario in €

In the optimal solution of the HR-scenario, all ports from the input rotation are visited. Just as in the RH-scenario, all transshipment locations are served by Rotterdam. Moreover, inland destinations Duisburg, Stuttgart, Munich and the Rotterdam/Antwerp-area are served by Rotterdam, and Vienna and the Hamburg/Bremerhaven-area are served by Hamburg. Serving all inland destinations by Rotterdam would lead to a significant cost increase of €18 per container (€439 versus €421 per container), due to the higher rail tariffs from Rotterdam to Vienna and the Hamburg/Bremerhaven-area.

Figure 7: Flow HR-scenario

ARBH-scenario	Flow
Deep sea	SHA $\xrightarrow{15497}$ RTM
	RTM $\xrightarrow{11454}$ BRV
	BRV $\xrightarrow{6250}$ DUM
Feeder	BRV $\xrightarrow{538}$ STP
	STP $\xrightarrow{42}$ GDY
	BRV $\xrightarrow{628}$ AAR
	AAR $\xrightarrow{340}$ GOT
	GOT $\xrightarrow{6}$ KRS
	BRV $\xrightarrow{1862}$ SOU
	SOU $\xrightarrow{1370}$ FXT
Rail	RTM $\xrightarrow{485}$ MUN
	RTM $\xrightarrow{1034}$ STU
	RTM $\xrightarrow{1211}$ DUI
	RTM $\xrightarrow{1313}$ RAA
	BRV $\xrightarrow{863}$ VIE
	BRV $\xrightarrow{1313}$ HBA

Table 17: Container flow ARBH-scenario

Rotation	Optimal	Input
Fixed cost	1.171.629	1.187.662
Fuel cost	1.306.708	1.339.935
Port call cost	199.001	382.154
Terminal handling cost	965.799	965.799
Transshipment cost	278.576	278.576
Rail cost	980.263	980.263
Transit time cost	1.424.237	1.489.887
Total cost	6.326.214	6.624.277
Cost per container	408	427

Table 18: Cost structure ARBH-scenario

In the optimal solution of the ARBH-scenario only Rotterdam and Bremerhaven are visited, and thus not all ports of the input scenario are chosen. All transshipment locations are served from Bremerhaven instead of Rotterdam, since the lower transshipment costs (€92 in Bremerhaven versus €112 in Rotterdam) and shorter distance to the Baltic and Scandinavia. Inland destinations that were served by Hamburg in the previous scenario are now served by Bremerhaven.

Figure 8: Flow ARBH-scenario

ARBHG-scenario	Flow
Deep sea	$\text{SHA} \xrightarrow{15497} \text{RTM}$
	$\text{RTM} \xrightarrow{11454} \text{BRV}$
	$\text{BRV} \xrightarrow{6250} \text{DUM}$
Feeder	$\text{BRV} \xrightarrow{538} \text{STP}$
	$\text{STP} \xrightarrow{42} \text{GDY}$
	$\text{BRV} \xrightarrow{628} \text{AAR}$
	$\text{AAR} \xrightarrow{340} \text{GOT}$
	$\text{GOT} \xrightarrow{6} \text{KRS}$
	$\text{BRV} \xrightarrow{1862} \text{SOU}$
	$\text{SOU} \xrightarrow{1370} \text{FXT}$
Rail	$\text{RTM} \xrightarrow{485} \text{MUN}$
	$\text{RTM} \xrightarrow{1034} \text{STU}$
	$\text{RTM} \xrightarrow{1211} \text{DUI}$
	$\text{RTM} \xrightarrow{1313} \text{RAA}$
	$\text{BRV} \xrightarrow{863} \text{VIE}$
	$\text{BRV} \xrightarrow{1313} \text{HBA}$

Table 19: Container flow ARBHG-scenario

Rotation	Optimal	Input
Fixed cost	1.171.629	1.250.786
Fuel cost	1.306.708	1.465.874
Port call cost	199.001	455.452
Terminal handling cost	965.799	965.799
Transshipment cost	278.576	278.576
Rail cost	980.263	980.263
Transit time cost	1.424.237	1.489.887
Total cost	6.326.214	6.886.638
Cost per container	408	444

Table 20: Cost structure ARBHG-scenario

For the ARBHG-scenario, we obtain the same solution as for the ARBH-scenario, that is, only Rotterdam and Bremerhaven are visited. Since we need a 16k TEU deep sea vessel to ship the current demand volume, sailing to Gdynia will be infeasible due to port capacity restrictions.

Figure 9: Flow ARBHG-scenario

RHR-scenario	Flow
Deep sea	SHA $\xrightarrow{15497}$ RTM
	RTM $\xrightarrow{8426}$ HAM
	HAM $\xrightarrow{6250}$ DUM
Feeder	RTM $\xrightarrow{538}$ STP
	STP $\xrightarrow{42}$ GDY
	RTM $\xrightarrow{628}$ AAR
	AAR $\xrightarrow{340}$ GOT
	GOT $\xrightarrow{6}$ KRS
	RTM $\xrightarrow{1862}$ SOU
	SOU $\xrightarrow{1370}$ FXT
Rail	RTM $\xrightarrow{485}$ MUN
	RTM $\xrightarrow{1034}$ STU
	RTM $\xrightarrow{1211}$ DUI
	RTM $\xrightarrow{1313}$ RAA
	HAM $\xrightarrow{863}$ VIE
	HAM $\xrightarrow{1313}$ HBA

Table 21: Container flow RHR-scenario

Rotation	Optimal	Input
Fixed cost	1.176.404	1.200.568
Fuel cost	1.316.181	1.364.390
Port call cost	214.614	239.068
Terminal handling cost	965.799	965.799
Transshipment cost	339.136	339.136
Rail cost	983.715	983.715
Transit time cost	1.409.878	1.409.878
Total cost	6.405.728	6.502.554
Cost per container	413	420

Table 22: Cost structure RHR-scenario in €

For the RHR-scenario, we obtain the same results as for the RH-scenario, since Rotterdam is not called a second time in the optimal solution. When calculating the total cost of the input scenario, we use a 75% rebate on port call costs for the second call in Rotterdam.

Figure 10: Flow RHR-scenario

RHfeeder-scenario	Flow
Deep sea	SHA $\xrightarrow{15497}$ RTM
	RTM $\xrightarrow{6250}$ DUM
Feeder	RTM $\xrightarrow{538}$ STP
	STP $\xrightarrow{42}$ GDY
	RTM $\xrightarrow{628}$ AAR
	AAR $\xrightarrow{340}$ GOT
	GOT $\xrightarrow{6}$ KRS
	RTM $\xrightarrow{1862}$ SOU
	SOU $\xrightarrow{1370}$ FXT
Rail	RTM $\xrightarrow{485}$ MUN
	RTM $\xrightarrow{1034}$ STU
	RTM $\xrightarrow{1211}$ DUI
	RTM $\xrightarrow{1313}$ RAA
	RTM $\xrightarrow{863}$ VIE
	RTM $\xrightarrow{1313}$ HBA

Table 23: Container flow RHfeeder-scenario

Rotation	Optimal	Input
Fixed cost	1.152.240	1.156.820
Fuel cost	1.267.972	1.276.787
Port call cost	129.024	156.911
Terminal handling cost	926.631	926.631
Transshipment cost	339.136	582.848
Rail cost	1.373.345	1.373.345
Transit time cost	1.366.485	1.366.485
Total cost	6.554.835	6.839.829
Cost per container	423	441

Table 24: Cost structure RHfeeder-scenario in €

From the optimal solution of the RHfeeder-scenario, it turns out feedering from Rotterdam to Hamburg is not cost efficient. The high costs of feedering are mainly caused by transshipment costs in Rotterdam.

Figure 11: Flow RHfeeder-scenario

In the ARBH-scenario, ARBHG-scenario, RHR-scenario, and RHfeeder-scenario not all permitted arcs are used in the optimal solution, and therefore sailing the whole rotation is inefficient in terms of total costs. The percentage gap between total costs in the optimal solution and total costs when sailing the whole rotation are 4.5%, 8.1%, 1.5%, and 4.2%, for the ARBH-scenario, ARBHG-scenario, RHR-scenario, and RHfeeder-scenario, respectively. In the ARBH-scenario, both Antwerp and Hamburg are not part of the optimal solution. We would like to know which port is the least expensive to add to our rotation. When adding only Antwerp to the optimal solution, we obtain a total cost of €421 per container, while adding only Hamburg results in a cost of €415 per container. In the ARBHG-scenario, it is not feasible to add Gdynia to the optimal solution, since it can only handle vessels up to 14.000 TEU.

Overall, we obtain the lowest total cost per container for the optimal solutions of the ARBH-scenario and ARBHG-scenario (€413). On the other hand, the total cost per container for sailing the input rotation of the ARBHG-scenario gives the highest cost per container of all scenarios (€444). Next to that, we observed that the choice of port(s) to call is heavily influenced by transshipment costs and rail costs. Fixed costs, such as ship operating costs, fuel costs, and port call costs seem to have a less significant effect on routing choice.

In Table 25 the throughput in Rotterdam is provided for each scenario. A distinction can be made between containers with a transshipment destination and containers with a hinterland destination. In the ARBH-scenario and ARBHG-scenario, zero containers are transshipped via Rotterdam, since Bremerhaven is a better option in terms of transshipment costs (€92 in Bremerhaven versus €112 in Rotterdam). In the other scenarios, all containers are transshipped via Rotterdam, as transshipment costs in Rotterdam are substantially lower than in Hamburg (€112 versus €170). Except for the RHfeeder-scenario, hinterland destinations are partly served by Rotterdam, as rail costs to Vienna and the Hamburg/Bremerhaven-area are substantially higher when served by Rotterdam opposed to German ports. Only in the RHfeeder-scenario, all hinterland destinations are served by Rotterdam.

Throughput	RH	HR	ARBH	ARBHG	RHR	RHfeeder
Transshipment	3.028	3.028	0	0	3.028	3.028
Hinterland	4.043	4.043	4.043	4.043	4.043	6.219
Total	7.071	7.071	4.043	4.043	7.071	9.247

Table 25: Container throughput in Rotterdam per scenario (in TEU)

6.2 Impact larger vessel

In this section we will investigate the effects of using a larger deep sea vessel while retaining the same demand volume on total costs per container and routing choice. Therefore we run our model with the same data as for the base case, except we restrict the model to use vessel type 6 (19k TEU) instead of the optimal vessel type. This is done by setting the capacities of vessel type 5 (16k TEU) to zero, such that vessel type 6 will be chosen automatically when solving the problem. In the first and second row of Table 26 total costs are displayed for all scenarios using a 19k TEU vessel, and it is indicated whether the same routing choice is made in the optimal solution as in the base case. In the third and fourth row, one can find total costs per container when using a 19k TEU vessel, and the additional costs per container when using a 19k TEU vessel instead of a 16k TEU vessel. In the RH-scenario and HR-scenario a different routing is chosen in the optimal solution, since sailing to Hamburg with a 19k TEU vessel is infeasible. We only allow sailing to Hamburg in case of a double call in Rotterdam (RHR-scenario), because export containers with origination Rotterdam are loaded on the vessel at the second call. The routing chosen in the optimal solution of the RHR-scenario is therefore the same as for a smaller ship type. The increase in total costs per container by using a bigger vessel is the largest for the RH-scenario, and the smallest for the ARBH-scenario, ARBHG-scenario, RHR-scenario, and RHfeeder-scenario. Since the deep sea routing when using a larger vessel stays the same for the ARBH-scenario, ARBHG-scenario, RHR-scenario, and RHfeeder-scenario, the container throughput and therefore also call size remain the same as in the base case. However, in the RH-scenario and HR-scenario the routing choice has changed for using a larger vessel. The throughput in Rotterdam therefore becomes 9247 TEU in total for both scenarios; 3028 TEU is transshipped, and 6219 TEU is transported to hinterland destinations. We conclude that using a 19k TEU vessel increases the throughput and therefore call size in Rotterdam for scenarios where Hamburg is called without a double call in Rotterdam.

Type 6	RH	HR	ARBH	ARBHG	RHR	RHfeeder
Total cost	6.813.354	6.813.354	6.585.362	6.585.362	6.673.511	6.813.354
Same routing?	No	No	Yes	Yes	Yes	Yes
Cost per container 19k TEU	440	440	425	425	431	440
Cost per container 16k TEU	413	421	408	408	413	423

Table 26: Effects of using a 19k TEU vessel instead of a 16k TEU vessel, costs given in €

6.3 Sensitivity analysis - demand

In this section we study the effects of fluctuations in demand volume on total costs per container and routing choice. As we did before in the preliminary analysis, we scale demand volume up and down by 15%. In Table 27 total costs are given per scenario when demand is scaled down by 15%, also referred to as low case demand. Next to that, it is indicated whether the routing choice stayed the same in the optimal solution for low case demand, compared to the base case. We observe that lowering demand does not influence the routing choice made in the optimal solution. For all scenarios, total cost per container decrease when demand is lower, since we are able to use a smaller, 14k TEU, ship.

In Table 28 total costs are given per scenario when demand is scaled up by 15%, referred to as high demand case. It is also indicated whether the routing choice stayed the same compared to the base case. When demand increases, the routing options found in the base case for the RH-scenario and HR-scenario are no longer feasible, and therefore Hamburg is skipped in the optimal solution for the high demand case. Routing options for the other scenarios stay the same. Except for the RH-scenario, total costs per container

Scenario	RH	HR	ARBH	ARBHG	RHR	RHfeeder
Total cost	5.383.807	5.476.012	5.312.639	5.312.639	5.383.807	5.501.683
Same routing?	Yes	Yes	Yes	Yes	Yes	Yes
Cost per container	409	416	403	403	409	418
Base case	413	421	408	408	413	423

Table 27: Costs per scenario for low case demand in €

Scenario	RH	HR	ARBH	ARBHG	RHR	RHfeeder
Total cost	7.432.428	7.432.428	7.154.902	7.154.902	7.246.622	7.432.428
Same routing?	No	No	Yes	Yes	Yes	Yes
Cost per container	417	417	402	402	407	417
Base case	413	421	408	408	413	423

Table 28: Costs per scenario for high case demand in €

are lower for a higher demand. For all scenarios, a 19k TEU vessel is chosen in the optimal solution. Remarkable is that for almost all scenarios, the costs per container are lower for both low and high case demand compared to the base case. This is due to the relation between demand volume and capacity of a vessel type. The more containers are loaded on a vessel, the lower the costs per container are. However, we must switch to a larger ship if demand volume exceeds the capacity of the vessel. This causes the inconsistency of costs per container when varying demand volume. Therefore we examine the effects of demand alterations in more detail for one specific scenario. We choose the ARBH-scenario to perform this extensive analysis on, since it has the lowest total costs of all scenarios. In Table 29 the effects of demand fluctuations on total costs for the ARBH-scenario are exhibited. For several demand factors, we determine total costs, costs per container and the vessel type used. We observe that costs per container decrease for increasing demand volume when using the same vessel type. When a larger vessel is needed, we observe a jump in total costs per container. Overall, the costs per container decrease, and a minimum of €402 per container is obtained for the largest demand volume.

We can now conclude that fluctuations in demand volume only affect routing choice and therefore throughput and call size in Rotterdam if demand is increased by such an amount that a 19k TEU vessel has to be used, and Hamburg is called without a double call in Rotterdam. Otherwise, the same routing is used as in the base case. When considering the ARBH-scenario, the routing choice stays the same as in the base case, even for very low demand volumes. Therefore, we may conclude that the call size in Rotterdam is only influenced by fluctuations in demand volume if Hamburg is called on the same rotation without a double call in Rotterdam.

6.4 Sensitivity analysis - bunker price

In this section we will examine the effects of fluctuations in bunker price on routing choice and total costs per container. To do so, we scale bunker prices, both IFO 380 and MGO, up and down by 15%. In Table 30 the bunker prices are scaled down by 15%, also referred to as low case bunker price. We observe the total costs per container decrease for every

Demand factor	0.35	0.45	0.55	0.65	0.75
Cost ARBH-scenario	2.731.080	3.102.084	3.992.011	4.344.452	4.697.583
Same routing?	Yes	Yes	Yes	Yes	Yes
Nr. containers	5.425	6.974	8.524	10.072	11.623
Cost per container	503	445	468	431	404
Ship type	2 (8k TEU)	2 (8k TEU)	3 (13k TEU)	3 (13k TEU)	3 (13k TEU)
Demand factor	0.85	0.95	1.05	1.15	
Cost ARBH-scenario	5.312.639	6.143.671	6.785.819	7.154.902	
Same routing?	Yes	Yes	Yes	Yes	
Nr. containers	13.174	14.722	16.271	17.819	
Cost per container	403	417	417	402	
Ship type	4 (14k TEU)	5 (16k TEU)	6 (19k TEU)	6 (19k TEU)	

Table 29: Cost of the ARBH-scenario for several demand volumes in €

scenario. Furthermore, the routing decision remains the same as in the base case for each scenario. In Table 31 we scale bunker prices up by 15%, and observe that total costs per container increase for every scenario. As for the low bunker case, routing choice stays the same when increasing bunker prices for each scenario. Next to that, a linear relationship between bunker price and total cost per container can be observed, although sometimes not clearly visible due to rounding. Since the results of this sensitivity analysis are quite trivial, we do not further investigate the effects of bunker price fluctuations into detail for a specific scenario. In conclusion, alterations in bunker prices do not affect the routing choice and therefore container throughput and call size in Rotterdam, irrespective of the scenario considered.

Scenario	RH	HR	ARBH	ARBHG	RHR	RHfeeder
Total cost	6.208.300	6.314.141	6.130.207	6.130.207	6.208.300	6.364.639
Same routing?	Yes	Yes	Yes	Yes	Yes	Yes
Cost per container	401	407	396	396	401	411
Base case	413	421	408	408	413	423

Table 30: Costs per scenario for low case bunker price in €

Scenario	RH	HR	ARBH	ARBHG	RHR	RHfeeder
Total cost	6.603.155	6.721.196	6.522.219	6.522.219	6.603.155	6.745.031
Same routing?	Yes	Yes	Yes	Yes	Yes	Yes
Cost per container	426	434	421	421	426	435
Base case	413	421	408	408	413	423

Table 31: Costs per scenario for high case bunker price in €

7 Conclusion

In this section we will establish our conclusions, provide further research directions, and discuss shortcomings of this research.

With the mixed integer programming formulation provided in this thesis, we are able to determine the optimal cargo allocation on a pre-specified deep sea rotation within a negligible amount of running time for our problem instance. Pre-specifying a routing scenario turns out to be very beneficial in terms of reducing calculation time, and we expect our model to run in a reasonable timespan also for larger problem instances. Another advantage of pre-specified scenarios is that we are able to easily compare existing deep sea routings with each other, and check whether it is beneficial to sail the whole rotation or skip one or multiple ports in the original scenario.

In the preliminary analysis, we observed that fluctuations in demand have quite a large effect on total costs. In our main model, however, these alterations do not effect routing and/or port choice for almost all instances. Fluctuations in demand volume only affect routing choice and therefore throughput and call size in Rotterdam if demand is increased by such an amount that a 19k TEU vessel has to be used, and Hamburg is called without a double call in Rotterdam. In these cases, Hamburg is skipped in the optimal rotation since it is not feasible to sail to Hamburg with a 19k TEU vessel without a double call. This causes the call size and throughput in Rotterdam to increase. Next to that, we studied the effect of overcapacity. As we expected, total costs per container are the lowest when the vessel is fully loaded. When less containers are loaded, the costs per container increase. Next to that, total costs per container are lower for a fully loaded 19k TEU vessel than for fully loaded smaller vessels.

From the preliminary analysis we concluded that alterations in bunker prices have a very limited effect on total costs. This observation is confirmed by the results of our overall model when varying bunker prices. Independent of the scenario considered, alterations in bunker prices do not affect the routing choice and therefore container throughput and call size in Rotterdam.

The use of an ultra large container vessel only leads to an increase in call size in Rotterdam for scenarios where Hamburg is called without a double call in Rotterdam, because sailing to Hamburg with such a large vessel is infeasible. A double call in Rotterdam will make sailing to Hamburg possible, since the vessel will have a smaller load. In other scenarios, the optimal routing remains the same when using a ULCS.

Concluding, fluctuations in bunker prices do not affect routing choices and therefore the call size in Rotterdam at all, while using an ultra large container vessel or increasing demand such that an ULCS is needed, affect the routing choice and call size in Rotterdam in case Hamburg is called in the routing without a double call. When Hamburg is not used in the rotation, or a double call in Rotterdam is used, a large demand volume or the use of an ULCS do not affect routing choices or the call size in Rotterdam. We also observed that calling many ports in one rotation is not beneficial in terms of total costs. For instance, in the ARBHG-scenario, only 2 out of 5 possible deep sea ports are called in the optimal solution. Even when demand volume is reduced such that a relatively small deep sea vessel can be used, and thus calling Gdynia is feasible, only 2 ports are called. This contradicts what we observe in practice: a relatively large amount of ports is called in one rotation, even with a large deep sea vessel.

When executing this research, we discovered that fixed costs such as port call cost, fixed operating cost, and fuel cost have a small influence on total costs, and are not likely to affect routing choices and therefore call sizes for our problem instance. On the contrary, costs incurred per TEU such as rail cost, terminal handling cost, and transshipment cost have a significant effect on routing choice. Terminal handling costs and rail costs determine which port is called in the rotation, and from which port to serve inland destination. The choice of hub port(s) from where transshipment destinations are served, are mainly determined by transshipment costs. These insights in cost structure are very meaningful for a container terminal operator. By performing further research into these costs, ECT would be able to improve its competitive position among other terminal operators, especially the German operators.

In this research, we do not take port visit frequencies into account. That is, we only consider one vessel rotation, and not a complete liner shipping network. For further research, it would be interesting to extend our model to multiple vessels and to impose constraints on port visit frequency. Furthermore, our model does not impose transshipment time when a container is transshipped from deep sea to feeder to avoid complexity. Including transshipment time in the model will make the results more realistic. Another shortcoming of this research is that most data is estimated, due to a lack of transparency in the market. Therefore, some data used in this thesis may not be accurate. To be able to draw conclusions about competitiveness, further research should be done to obtain more realistic data, in particular for costs per TEU, i.e. rail cost, terminal handling cost, and transshipment cost. Next to that, we only consider the import of containers, and neglect the export of containers. In reality, inbound and outbound container flow is intertwined, i.e. when import containers are unloaded in a port, export containers are loaded in the same port call. Including also export container flow in the model, will lead to a more realistic representation of reality. By using routing scenarios as input in our model, we are able to obtain an optimal solution in a negligible running time for our problem instance. We expect the model to run in a reasonable timespan even for larger problem instances. Due to the complexity of the liner shipping network design and cargo routing problem, this is a valuable contribution to existing methods for these problems.

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A Appendix

Dist(mile)	SHA	ANR	RTM	BRV	HAM	DUM	STP	GDN	AAR	GOT	KRI	SOU	FXT
SHA	0	13797	13800	14003	14059	13756	15047	14631	14316	14231	14150	13579	13756
ANR	13797	0	121	333	386	200	1386	970	655	570	488	260	141
RTM	13800	121	0	256	307	200	1305	889	574	489	413	261	121
BRV	14003	333	256	0	109	200	1178	762	447	362	292	464	367
HAM	14059	386	307	109	0	200	1218	802	487	402	333	522	411
DUM	13756	200	200	200	200	0	200	200	200	200	200	200	200
STP	15047	1386	1305	1178	1218	200	0	578	819	838	950	1508	1336
GDN	14631	970	889	762	802	200	578	0	406	463	534	1092	920
AAR	14316	655	574	447	487	200	819	406	0	139	219	777	605
GOT	14231	570	489	362	402	200	838	463	139	0	134	692	520
KRI	14150	488	413	292	333	200	950	534	219	134	0	611	525
SOU	13579	260	261	464	522	200	1508	1092	777	692	611	0	382
FXT	13756	141	121	367	411	200	1336	920	605	520	525	382	0

Table 32: *Distance in mile between ports*

SHA	Shanghai
ANR	Antwerp
RTM	Rotterdam
BRV	Bremerhaven
HAM	Hamburg
DUM	Dummy
STP	St Petersburg
GDY	Gdynia
AAR	Aarhus
GOT	Gotenborg
KRS	Kristiansand
SOU	Southampton
FXT	Felixstowe
MUN	Munich
STU	Stuttgart
DUI	Duisburg
VIE	Vienna
RAA	Rotterdam/Antwerp area
HBA	Hamburg/Bremerhaven area

Table 33: *List of abbreviations*

	Value 20ft container
Fashion accessories	58 440
Retail apparel	90 930
Furnishings	15 995
Electronics	84 451
Toys	49 050
Organic chemicals	43 315
Average	57 030

Table 34: *Container value for several goods in €*

Ship	Type	Name
1	Feeder	Unifeeder Spica J
2	DS	MOL Charisma
3	DS	Hanjin Europe
4	DS	MSC Valeria
5	DS	CMA CGM Marco Polo
6	DS	MSC Oscar

Table 35: *Vessel type and name*