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Constructing service networks in liner shipping

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Abstract

Seaborne shipping is the most important mode of transport in international trade. After years of continuous growth, world seaborne trade volumes fell in 2009. However, signs of recovery can be observed, so seaborne trade is expected to recover. Current service networks should probably be reconsidered, because, for example, the financial crisis has caused an enormous rise in the oil price. In this thesis a model is proposed that can be used to construct new liner shipping service networks. This service network has to consist of a set of routes. For each route, the ship type and sailing speed used to serve the route have to be determined together with the cargo allocation on the route.

First, a linear programming model is formulated that determines the optimal cargo allocation of a given set of routes. The performance of this model is compared to the performance of some heuristics. The optimal model proposed in this thesis performs on average more than 20% better than the heuristics.

To determine the best service network, a genetic algorithm based approach is provided in this thesis. However, because the linear programming model that determines the cargo allocation has to be solved repeatedly, this approach will become too time consuming when the size of the problem is not decreased. Therefore, an aggregation method is described in this thesis that divides the ports in a few clusters. In this way, the method can be performed in a reasonable amount of time. However, the results have to be disaggregated after the linear programming problem is solved. Therefore, also a disaggregation method is proposed together with some improvement steps.

The data used in this thesis are mainly based on the Asia-Europe tradelane of Maersk during spring 2010. Therefore, this method is used as a reference network in this thesis. Furthermore, an upper bound on the profit that can be obtained is calculated.

The profit of the best network found in this thesis is 43% away from the upper bound. However, it is an improvement of about 40% compared to the reference network.

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Chapter 1

Introduction

Seaborne shipping is the most important mode of transport in international trade. More than 80% of the international trade in 2010 is transported over sea (UNCTAD (2010)). In comparison to other modes of freight transport, like truck, aircraft, train and pipeline, ships are preferred for moving large amounts of cargo over long distances.

In the shipping market, three types of operations are distinguished, tramp shipping, industrial shipping and liner shipping (Lawrence (1972)). Tramp ships do not have a fixed schedule and are used for immediate deliveries where the most profitable freight is available. Therefore, the activities in tramp shipping are very irregular. In industrial shipping the cargo owner controls the ship and the objective becomes to minimize the cost of shipping. In liner shipping, ships follow a fixed route within a fixed time schedule; this is most common in the container trade.

In this thesis, the focus will lie on the liner shipping market. The decision making in liner shipping can be distinguished on three different levels: the strategic, tactical and operational planning levels (Agarwal and Ergun (2008)). In the strategic planning level the optimal fleet-design is determined. This means that both the optimal number of ships in a fleet and the optimal ship sizes are determined in this level. This stage is very important, because the capital and operating cost in the (liner) shipping industry are very high. The ship-scheduling problem is solved in the tactical planning level. In this level, the service network is designed by creating ship routes and allocating the available ships to this routes. Finally, in the operational planning stage, it is determined which cargo is transported and which route(s) are used to ship the cargo. This problem is also referred to as the cargo-routing problem. The decisions made in a planning level influence the decision making in the other levels. Therefore, it could be profitable to solve the problems on the different levels simultaneously.

1.1 Research problem

After a long period of growth, world seaborne trade volumes fell by about 4.5% in 2009. This is caused by the economic downturn as a consequence of the global financial crisis late 2008 (UNCTAD (2010)). However, because signs of recovery can be observed, international seaborne trade is expected to recover and grow in 2010. The recession of 2008-2009 and the recent unrest in the Middle East have caused an enormous rise in the oil price. Because the profit of liner shipping companies highly depend on the demand and oil price, current networks should probably be reconsidered. In this thesis, it is investigated whether an optimal network can be found that maximizes the profit of a liner shipping company.

The problem considered in this thesis is the combined fleet-design, ship-scheduling and cargo-routing problem. According to the levels of decision making described in Agarwal and Ergun (2008), all three levels are considered at the same time. The objective in this thesis is to design a service network that maximizes profit, given some demand and cost data.

The service network should consist of

- a set of routes (string of ports that are visited in consecutive order)
- the allocation of ships to the included routes
- the speed of the ships allocated to a route
- the demand allocation over the included routes.

The main research question in this thesis is:

- *How can mathematical programming techniques and/or heuristics be used to solve the combined fleet-design, ship-scheduling and cargo-routing problem?*

Mathematical programming leads to exact solutions, which is preferred in many problems. For many mathematical programming techniques high-performance solvers are available. However, solving problems using mathematical programming can be very time consuming. Heuristic methods can then be used to reduce the computational time. However, a disadvantage of heuristics is that the obtained solution is most probably not optimal. Furthermore, in many cases it is hard to estimate how far the obtained solution lies from the optimum. Another advantage of mathematical programming techniques compared to heuristics is that the problem can in general relatively easily be extended when using mathematical programming. Therefore, in this thesis first mathematical programming techniques are considered. When the computational time becomes too high or the problem cannot be solved using only mathematical programming techniques, heuristics are introduced to solve (parts of) the problem. The mathematical programming techniques considered in this thesis are linear programming, mixed integer programming and column generation.

To solve the problem using the mathematical programming techniques mentioned above, the problem (or at least a subproblem) have to be formulated as a linear or mixed integer programming problem. If the total problem can be formulated as one mixed integer problem, the solution of the linear programming relaxation can give useful information on the upper bound of the profit. Therefore, the following subquestions can be formulated in order to answer the main research question.

1. Can one or more of the subproblems (fleet-design, ship-scheduling and cargo-routing) be formulated as a linear or mixed integer programming problem?
2. Can the combined fleet-design, ship-scheduling and cargo-routing problem be formulated as one mixed integer problem?
    (a) If such a formulation can be found, can the linear programming relaxation of the formulation in subquestion 1 then be solved and used as upper bound on the profit?

In some researches the cargo-routing problem is solved heuristically. These heuristics provide solutions in a short time, but most of times it is unknown how far the obtained solution is from the optimal solution. When the performance in both profit and computational time of known heuristics is compared to the performance of the linear or mixed integer programming problem for the cargo-routing problem, a trade-off between these methods can be made. Of course, this is only relevant when the cargo-routing problem can be formulated as a linear or mixed integer programming problem. Furthermore, when the cargo-routing problem can be formulated as a linear programming problem, it is a candidate master problem for a column generation approach. Further, to implement as a column generation algorithm, the total problem has to be formulated a mixed integer problem. This implies that if the subquestion 2 is answered negatively, a column generation approach is not possible for the problem. Now, the following new subquestions are obtained:

3. What is the performance of some known heuristics compared to the linear or mixed integer programming solution of subquestion 1?
4. Can the linear programming formulation of subquestion 1 be used as master problem of a column generation approach?

If the total problem cannot be solved using only the mathematical programming techniques mentioned above, other methods have to be investigated. When too much time is needed to solve the problem, it may be useful to decrease the size of the problem in order to obtain smaller problem instances, which can be solved using mathematical programming techniques (possibly in combination with heuristics). Heuristic methods will then be used to decrease the problem size and convert the obtained solution to the initial problem size. The following subquestions can now be defined.

5. Can the size of the problem instances be reduced in order to increase the speed of the solution method?
    (a) If the problem size can be reduced, can the smaller problems be solved using only mathematical programming techniques?
    (b) Which methods can be used to convert the solution to the initial problem size?
    (c) If the smaller problems still cannot be solved using only mathematical programming techniques, can these problems then be solved using a combination of mathematical programming techniques and heuristics or using only heuristics?

Finally, the model described in this thesis can be used to solve the combined fleet-design, ship-scheduling and cargo-routing problem. It is tried to calculate an upper bound on the profit to which the best obtained profit can be compared. Furthermore, one feasible service network will be defined as reference network. Then, the performance of other service networks can be compared with the performance of the reference network. Now, the last subquestions can be formulated:

6. Can a good upper bound on the profit be determined?
    (a) What is the performance of the best service network found in this thesis compared to the upper bound?
7. Which service network can best be defined as reference network that can be used to compare with other networks?
    (a) What is the performance of the best service network found in this thesis compared to the reference network?

1.2 Structure

The remaining of this thesis is organized in the following way. The next chapter gives an overview on relevant literature. Furthermore, the solution approaches provided in the literature are evaluated. In chapter 3, a detailed description of the problem investigated in this thesis is given as well as an overview on the data needed to solve the problem . Furthermore, a list of assumption made in this thesis is provided in chapter 3. Thereafter, chapter 4 gives an overview of the available data.

Chapters 5-9 describe the model used in this thesis. In chapter 5 a linear programming formulation is provided that can be used to solve the cargo-routing problem. Furthermore, three heuristical methods that solve the cargo-routing problem are given and their results are compared to the results of the LP model. Next, in chapter 6, methods to aggregate and disaggregate ports are described. Aggregating ports into port clusters decreases the problem size, which leads to a decrease in computational time. After the model is solved, the results have to be disaggregated to individual port results. Furthermore, some improvement steps are described in chapter 6. Thereafter, in chapter 7, a method is provided that can be used to design initial feasible service networks. Furthermore, it is described how the optimal speed of each route in a service network can be determined. Then, chapter 8 describes a genetic algorithm based approach to change existing service networks into new service networks. Finally, chapter 9 proposes a method to determine an upper bound on the profit and defines a reference network that can be used to compare with other networks.

Chapter 10 gives an overview of the main results obtained in this thesis. Characteristics of the best service network found are given and compared to the reference service network. Thereafter, in chapter 11 a conclusion is formulated. Finally, chapter 12 gives a discussion on the methods used and results obtained in this thesis together with some subjects for further research.

Chapter 2

Literature review

The last decades, maritime transport has become a more popular field of research. In 1983 the first survey on ship routing and scheduling was published (Ronen (1983)). This survey gives a detailed overview on the research performed on ship routing and scheduling in the period before 1983. However, the author states that relatively little work has been done in ship routing and scheduling. In this survey the author also discusses the major differences between vehicle and ship routing and scheduling. Furthermore, several explanations for the low attention to ship scheduling in the years before this article was written are given. Finally a classification of ship routing and scheduling problems and models is given in this article.

Next, Ronen (1993) is a survey on ship scheduling and related problem in the period from 1983-1993. Again, the author provides a detailed summary of published research in this area. Furthermore, the development in the realization of solutions is discussed in this article. The widespread availability of computers makes it possible to obtain better solutions and reduces the computation times.

The last survey discussed in this thesis is Christiansen et al. (2004). The survey describes the major developments in the ship routing and scheduling problems in the period from 1994-2004. The authors divide the reviewed papers in four categories. They conclude that little research has been performed on liner shipping, even though liner shipping became more and more important during the reviewed period. In the second part of the paper, the authors discuss some trends in the shipping industry that need further research. Furthermore, they give a few new research directions within the shipping industry.

In the remaining of this chapter a review on the most relevant literature on fleet-design, ship-scheduling and cargo-routing is given. Furthermore, some literature on comparable problems in other transportation modes is discussed. In the final section of this chapter, the solution approaches are evaluated.

2.1 Fleet-design and cargo-routing

This literature discussed in this section provides a solution method of one of the subproblems as described in chapter 1. The subproblems highly depend on each other, so they are hard to solve independently. Therefore, little research can be found in which only a subproblem is viewed.

In Fagerholt (1999) a 3-phase solution approach is considered to determine the optimal fleet size. The method can also be used to solve fleet composition problems when some assumptions are satisfied.

In the first phase all feasible routes for the largest ships are generated and ships of maximum size are allocated to the routes. Many routes will not use the total capacity, so the ship size can be reduced for those routes. Finally, for each route the ship that can serve the route with the least cost is selected.

In the second phase, single routes are combined, which means that those routes are performed subsequently. The total time of the combined routes cannot exceed one week. The ship size needed for combined routes is the largest ship size of the single routes that are combined.

In the third and last phase the problem of deciding the optimal fleet is formulated as a set partitioning problem, which is also solved in this phase.

For small problem instances, a solution of the fleet design problem can quickly be found. However, when the size of the problem instance increases, the computational time needed to solve the problem increases exponentially.

Then, Powell and Perakis (1997) use an integer programming model to optimize the fleet deployment for a liner shipping company. They compare the results to the results obtained with a linear programming model. When using a linear programming model, manipulation of the results is needed to guarantee integer solutions. This will result in suboptimal solutions, where the integer programming model always give the optimal solution. However, all possible routes have to be enumerated to solve the model optimally. This will probably make the model very time consuming when the problem becomes larger.

In Song et al. (2005) a cargo allocation model with two objectives is discussed. The first objective is to minimize the unassigned cargo volume. The second objective is to minimize total costs corresponding to a given minimal unassigned cargo volume. Because the model is very difficult to solve by analytical methods, the solution space is first truncated. Thereafter, the authors select priority rules and make use of heuristics to find solutions of the model.

2.2 Combined ship-scheduling and cargo-routing problem

Research on the combined ship-scheduling and cargo-routing problem is discussed in this section. Both literature on mathematical programming techniques and heuristical approaches is viewed.

In Rana and Vickson (1991) a mixed integer nonlinear programming (MINLP) problem is formulated to solve the combined ship-scheduling and cargo-routing problem. The objective of the MINLP problem is to maximize total profit for multiple ships.

The problem is solved by using a Lagrangean relaxation in which the complicating constraints are relaxed. This results in several subproblems that have to be solved. However, each subproblem is also a mixed integer nonlinear problem, so the subproblems are also decomposed to deal with the nonlinearity. In this way, several mixed integer linear programs are obtained, which are independently solved using a procedure in which all solutions above a certain threshold value are saved and added to a master problem. By solving the master problem, Lagrange multipliers are obtained, which are incorporated in the objective functions of the linear problems. Thereafter, the linear problems are solved again and the whole process is repeated until certain conditions are satisfied.

The authors report that their solution method can solve instances with up to 20 ports within an hour. However, the computational time increases rapidly as the number of ports increase.

Fagerholt (2004) presents an integer programming problem to solve the combined ship-scheduling and cargo-routing problem. In the solution method, first all feasible routes are generated and the cost and duration of the routes are determined. These routes are the input of the integer programming problem. The objective of the integer programming problem becomes to minimize the total operating cost for the whole fleet. The disadvantage of this method is that the number of candidate routes increases exponentially with the number of ports included in the problem, which increases the computational time and can lead to memory problems.

Hsu and Hsieh (2006) formulate a two-objective model to determine the optimal ship size and sailing frequency. The authors distinguish between shipping costs and inventory costs. The two objectives of their model are then minimizing shipping costs and minimizing inventory costs.

The model is solved to a Pareto optimum, which means that none of the two costs can be lowered without causing the other cost to raise. The authors consider two ways to transfer containers from their origin to their destination port: through a hub or directly. The routing decision is made by comparing the Pareto optimal solutions of both routing strategies. The routing strategy with the lowest Pareto optimal costs is preferred.

Thereafter a case study is performed to a simplified hub-and-spoke network. The example considers only one main line and three feeder lines. The main goal of the example is to illustrate the analysis of the routing, ship size and sailing frequency decisions.

Agarwal and Ergun (2008) also introduce a mixed integer model to solve the combined ship-scheduling and cargo-routing problem. Three methods are introduced to solve the problem.

First, a greedy heuristic is presented in which costs are assigned to each cycle that can be served. Then the minimum cost cycle is determined and is added to the solution if the cost is negative. This is repeated until all ships or demand are allocated or until no negative cost cycles exist anymore.

Next, a column generation-based algorithm is introduced. In this algorithm, first the master problem is solved. Thereafter, negative cost cycles are found and added to the solution. This procedure is repeated until no negative cost cycles can be found anymore. Then the integer program is solved using a branch-and-bound procedure.

The last method that is presented in Agarwal and Ergun (2008) is a Benders decomposition-based algorithm. In this method the problem is solved using a master problem and a sub-problem. In the MIP problem, the number of variables increases as the number of ports, ships and demand triplets increases. In the new introduced master problem, the number of variables increases as the number of cycles increases. Furthermore, the number of variables in the subproblem increases as the number of demand triplets increases. The increase in the problem size is thus divided between the master and the subproblem. In this method, a linear programming relaxation and a branch-and-bound procedure are used to solve the problem.

In Álvarez (2009) a mathematical programming formulation is presented to determine the optimal routes and deployment of a fleet of container vessels jointly. The joint routing and fleet deployment problem is formulated as a mixed integer programming (MIP) model. However, solving the MIP model for realistic instances of the problem will become very time consuming. Therefore, the author propose a two-tier approach to solve the problem.

In each iteration a specific vessel deployment is considered. When the vessel deployment is fixed, the MIP model is reduced to a multi-commodity flow problem (MCFP). The MCFP is a network flow problem where multiple commodities are considered with different origins and destinations. The author states that optimization codes exist, which can quickly solve very large instances of MCFP. Thereafter, utilization rates are computed, which are used to increase or decrease vessel sizes. Finally, a column generation approach is used to find a set of new possibly beneficial routes. The column generation approach is done in a heuristic way.

The article compares the above described algorithm with an exact branch and bound algorithm that is directly applied to the MIP model. The author concludes that the proposed algorithm can generate very good solutions in a short amount of time.

The method proposed in Man (2007) to solve the joint ship-scheduling and cargo-routing problem consists of three parts. First, the traveling salesman problem is solved using a heuristic method to determine the order in which ports are visited. In the next step, a variant of the set covering problem is solved to generate a starting set of routes that covers all demand. The last step consists of the allocation of demand to the routes taking the capacity into account.

Van de Weerd (2009) uses a similar approach as described in Man (2007). Some improvements in the set covering problem and the allocation method are presented, which lead to an increase in overall profit.

Van der Meer (2009) proposes an algorithm in which first for all possible routes the profit is calculated. Thereafter, the route with the highest profit is added to the solution and the demand satisfied by the route is subtracted from the demand matrix. Then, the profit of all remaining possible routes are again calculated. This process repeats until no profitable routes can be found anymore.

Next, a randomized selection algorithm is introduced to increase the profit. The new algorithm is based on the idea that each time selecting the most profitable route will not always lead to the best solution. Combinations of less profitable routes can be more profitable together. Therefore, in the randomized algorithm the most profitable R routes are selected. Thereafter, one of the routes is randomly selected and added to the solution. Indeed the profit increases when the randomized algorithm is used in stead of the first proposed basic algorithm.

Lachner and Boskamp (2011) provide a heuristical approach in which first a set of initial possible service networks is generated. Thereafter, a local search algorithm is used to improve the service networks.

In order to construct initial possible service networks, routes are randomly generated and a small part of the cargo is randomly assigned to these routes until an arbitrarily defined number of routes is reached. The remaining cargo can be assigned using two different methods. One of the methods is chosen at random.

The first method is based on the quantity of demand. The origin destination pair with the highest demand is selected and allocated to the route that serve both origin and destination and has the highest remaining capacity. Thereafter the demand and remaining capacities are updated. This process is repeated until no remaining capacity is available on all routes and all demand pairs are considered.

The other method is a profit-driven approach. In this method, for each demand pair all feasible routes are determined. Thereafter, a score is allocated to each route. The score indicates how profitable a route is for the selected demand pair. Finally, the demand is allocated to the route that is most profitable according to the scores.

In the local search algorithm, first inactive ports are removed from the routes. Ports are inactive when no demand is (un)loaded in the port when it is visited on a certain route. Thereafter, three operators are used to perform small changes to the solution.

The first operator influences the route length. With this operator a port is added to or removed from a route. This is only done when it is profitable to do so. When a port is removed from a route, demand that was allocated to or from this port is stored in an unassigned demand matrix.

The second operator tries to improve routes by exchanging ports. Both intra-route and inter-route port exchanges are considered. The intra-route port exchange means that a port that is currently visited on the east-bound trip will be visited on the west-bound trip after the exchange or vice versa. Inter-route port exchanges can be made in three different ways. A port that is visited on two different routes can be merged under certain conditions, so that it is only visited on one of the routes after the port exchange. Next, a port that is visited on only one of two routes can be exchanged to the other route. Finally, the turning port of a route can be removed from the route in which case the demand from and to that port will be reallocated to another route that visits this port. Again, all changes are only made when they are profitable.

The last operator is a transhipment operator. Until this point, all demand is directly served from the origin to the destination port (origin and destination port are visited on the same route). Now, it is investigated whether it is profitable to serve some demand pairs by more than one route.

Finally, Lachner and Boskamp (2011) provide an overview of results with several parameter settings. The authors claim that the best profit found using the method described above is within 13.5% of the optimal profit.

2.3 Comparison with other transportation modes

In other transportation modes problems occur that are comparable to the design of a service network in liner shipping. In this section, literature on airline scheduling and railway line planning is discussed and the problems are compared to liner shipping problems.

2.3.1 Airline Scheduling

In Grosche and Rothlauf (2008) a method is derived to optimize airline schedules. The authors state that no solution approaches exist in which airline schedules are constructed and optimized in a single model. Instead, airline schedules are usually constructed by decomposing the problem in several subproblems. The major subproblems according to the authors are flight schedule generation, fleet assignment, aircraft routing and crew scheduling.

In the flight schedule generation problem it is decided which flights are offered to the passengers. This includes the determination of the departure and arrival times. The flight schedule generation problem is thus comparable to the problem of designing routes in liner shipping.

The objective of the fleet assignment subproblem is to find an assignment of aircraft types to each flight in such a way that total operating costs and opportunity costs of lost revenue are minimized. The next subproblem, aircraft routing, has as objective to find an assignment of physical aircrafts to each flight leg in such a way that the profit is maximized. In liner shipping, these problems are comparable to the problem of allocating ships to the routes. The major difference is that in most liner shipping models, opportunity costs are not considered.

Finally, in the crew scheduling subproblem, an optimal assignment of crew members to the flights is determined. This problem is not considered in most liner shipping models.

The main differences between the liner shipping and airline industries are that in the shipping industry the optimal cargo allocation has to be determined by the shipping companies. Shipping companies can thus decide the optimal route of the cargo they transport. However in the airline industry, passengers book their journeys themselves. Each passenger chooses his own optimal route; the airlines do not have influence on the routes passengers travel. Furthermore, the routing process is much more complex in the shipping industry, because ships visit a string of ports on a route. Aircrafts fly usually direct from the origin to the destination airport. Finally, crew scheduling is less important for shipping companies.

After the division in subproblems is explained, a solution approach to solve the overall problem except the crew scheduling simultaneously is provided. The authors claim that this is the first integrated solution approach. The overall problem has always been solved by decomposing it into smaller subproblems. Three approaches are discussed in the remaining of the article: a threshold accepting algorithm, a selecto-recombinative genetic algorithm and a genetic algorithm.

The threshold accepting algorithm is a local search algorithm in which better solutions are always accepted and worse solutions are accepted with a certain probability. In each iteration a solution is considered that is in the neighborhood of the current solution, so only small changes are made.

The selecto-recombinative genetic algorithm is a recombination-based search in which two solutions are selected and recombined into a new solution. The worst solution in the solution set is then replaced by this new solution.

The genetic algorithm is a local and recombination based search in which a neighboring solution is created and evaluated with a certain probability. The other possibility is that two solutions are selected and recombined into a new solution. Again the new solution will replace the worst solution of the solution set. In the beginning mainly recombination is applied to explore the search area. The probability of selecting local search operators increases with the number of iterations.

The genetic algorithm leads to the best results, so a combination of local and recombined search is most effective in this problem. Furthermore, the authors conclude that the three solution approaches discussed in the article make it possible to solve integrated subproblems of the overall problem. This has the advantage that the several subproblems and their interdependencies are solved according to the overall objective.

In Desaulniers et al. (1997), a related problem in the aircraft industry is considered. In the article the problem of determining a daily fleet schedule that maximizes profits given a heterogeneous aircraft fleet is considered. The fleet has to cover a set of operational flight legs with given departure windows and durations. Two approaches to solve the problem are presented: a set partitioning formulation and a time constrained multi-commodity network flow formulation. The problems are solved by a combination of a branch-and-bound approach and a column generation (set partitioning) or Dantzig-Wolfe decomposition (multi-commodity network flow) approach. The subproblems in both the column generation and Dantzig-Wolfe decomposition approaches become longest path problems. The solution methods are used to solve the fleet-design problem European airline. The authors find an increase in profit improvement of almost 11% when their method is used.

2.3.2 Railway line planning

In Claessens et al. (1998) and Goossens et al. (2004) railway planning problems are discussed. The concept of the railway line planning problem is the same as that of the combined ship-routing and cargo-routing problem. The railway line planning problem can be defined as follows:

Given the railway infrastructure between stations, the traveler flows on each track, the operating costs associated with the exploitation of trains, and service and capacity constraints, determine a cost optimal allocation of lines to passenger flows. The allocation of lines involves the determination of the origin and destination stations of the lines with their frequencies per hour and the length of the trains on each line. (Claessens et al. (1998))

Thus, the goal of both the railway line planning problem and the combined ship-scheduling and cargo-routing problem is to select the stations/harbours at which trains/ships have to stop in such a way that passengers/loads can be optimally transported with respect to a certain objective function and some restrictions. Although both problems have a different objective function (minimize costs and maximize profit respectively), this will not lead to a different approach of the problems.

In Claessens et al. (1998) and Goossens et al. (2004) the passenger flow between each origin and destination station is split in different flows for different possible connections. Some variation in the flows is allowed, but the flows are more or less given for each connection. The major difficulty in this model is to construct lines in such a way that all passenger flows can be transported.

In the cargo allocation problem on the other hand, the determination of the path that is traveled by the load is a major difficulty in the model. Furthermore, demands do not have to be satisfied in the cargo allocation model, so the demands that will lead to the highest profits have to be selected.

2.4 Evaluation

The problem considered in this thesis is very similar to the problems considered in the reviewed literature. One of the main differences between the problem considered in this thesis and the problems on designing liner shipping service networks in the articles is that most of the articles solve the service network design problem assuming that the liner company already owns a fleet of vessels. In this thesis, the fleet of vessels has still to be constructed. Another difference is that most articles assume that all vessels sail with the same speed, while in this thesis, the speed is also optimized.

Also the articles on airline scheduling and railway line planning show similarities with the problem in this thesis. One of the main differences between the aircraft and the liner shipping industries is that the routing process is much more complex in liner shipping. Despite this differences, it is expected that the methods applied to the problems in literature are also promising for the problem in this thesis.

However, the approach used in railway line planning cannot be used for the combined ship routing and cargo allocation approach. This is caused by a different treatment of the passenger/load flow.

The solution approach discussed in Fagerholt (2004) can be useful to determine the optimal service network and fleet deployment for small problem instances. However, when the size of the problem instances increases, the computational time increases rapidly.

Based on the literature column generation and genetic algorithm are the most promising approaches for this problem. For this reason, in this thesis, it is chosen to construct a model that is able to optimally allocate the cargo to the available ships, when the ship schedules are known. Then it is tried to use a column generation approach with this model as master problem. If this is not possible, a genetic algorithm will be constructed that generates feasible ship schedules and computes the associated optimal cargo allocation and profit. Then, the algorithm will generate new feasible ship schedules and this process will be repeated until a certain stopping criteria is met.

Chapter 3

Problem definition

In the introduction, the research problem is already shortly introduced. In this chapter, the problem is defined in more detail. In the first section, a general description of the problem is given. First, a description of the three individual problems are given, thereafter the combined problem is formulated. In the next section, some characteristics of the data needed to solve the problem are given. In the last section, the assumptions made to model the problem are discussed.

3.1 Problem formulation

The problem considered in this thesis is the combined fleet-design, ship-scheduling and cargo-routing problem. In this thesis, the problem is solved for one liner shipping company, so competition between companies is not considered. In this section, first the three individual problems are described. Thereafter, a formulation of the combined problem is given.

3.1.1 Fleet-design problem

The goal of the fleet-design problem is to determine the optimal composition of the fleet. In this problem, both the number and the size of ships in the fleet have to be determined. For the shipping company it is important to determine the optimal fleet design, because the costs related to the fleet are very high. Costs related to the fleet composition can be distinguished in two types: fixed cost (capital and operating cost) and variable cost (fuel cost).

The underlying route network and demand have to be considered when determining the fleet composition of a liner shipping company. However, the fleet design is determined for 10-20 years, because of the high cost incurred by replacing a ship. In such a period, the demand structure can change, which can cause changes in the route network. Therefore, when determining the optimal fleet design, both present and future demand have to be considered.

Economies of scale are another important factor in purchasing new ships. Larger ships usually have lower transportation cost per TEU than smaller ships. However, the fixed cost of larger ships are higher than that of smaller ships. The demand on the route that the ship will serve also influence the decision of the ship size.

Thus, the fleet-design problem is hard to solve as an individual subproblem, because it highly depends on the results of the ship-scheduling and cargo-routing problems. Furthermore, the fleet-design problem is determined for 10-20 years, so also the results of the ship-scheduling and cargo-routing problems in future years influence the optimal fleet-design. Therefore, research question 1 has to be answered negatively for the fleet-design problem.

3.1.2 Ship-scheduling problem

In the ship-scheduling problem, the service network has to be designed. A service network consists of a set of ship routes and the allocation of ships to the routes. Furthermore, the optimal sailing speed has to be determined for each ship route. A ship route is a sequence of ports that are visited by a ship. The ship routes are cyclic, so the begin and end port are the same.

The allocation of ships to routes can be restricted, because for example a port on the route cannot handle a certain type of ship. Once a ship is allocated to a certain route, it will serve this route during the whole planning horizon. Most shipping companies operate schedules in which each route is served once a week to maintain a customer base and to provide customers with a regular schedule Agarwal and Ergun (2008). Therefore, in general the number of ships needed for one ship route has to be at least equal to the number of weeks needed to complete an entire round tour (rounded above).

The demand between ports influences the design on the optimal ship routes. However, the shipping company can choose to reject part of the demand, if that will increase their profit. This is decided in the cargo-routing problem. Therefore, the ship-scheduling and cargo-routing problems are often solved at the same time.

The ship-scheduling problem cannot be solved to optimality when the results of the cargo-routing problem are not known yet. Therefore, research question 1 also has to be answered negatively for the ship-scheduling problem.

3.1.3 Cargo-routing problem

In the cargo-routing problem, the shipping company makes two decisions. They decide which demands they accept and which routes are used to transport this cargo from the origin to the destination port. When the cargo-routing problem is solved as an individual problem, the service network is known on forehand. As already mentioned, in this thesis the profit is maximized for one shipping company, so competition is not investigated.

The goal of the cargo-routing problem is to maximize the profit. Revenues are obtained by transporting cargo between their origin and destination port. However, costs are also incurred by the transportation of the cargo. For some demand pairs the revenue that can be obtained will not exceed the cost incurred by transporting the cargo. This demand will then be rejected by the shipping company. Furthermore, it is possible that some profitable demands are rejected because other demands are more profitable.

When the demand of a demand pair is (partly) satisfied, the cargo will be picked up in the origin port and delivered at the destination port. When the origin port is visited on several ship routes, it has to be determined to which route the cargo is allocated. The same holds for the destination port. Some origin and destination ports will be visited on the same ship route, while others have to be transhipped to other routes. All these decisions are made in the cargo-routing problem.

3.1.4 Combined fleet-design, ship-scheduling and cargo-routing problem

The decisions made in the three individual problems affect the decision making in the other problems as well. For example, when the service network is determined in the ship-scheduling problem, the network structure and capacity limits for the cargo-routing problem are set. This implies that a bad choice of service network in the ship-scheduling phase can result into lower profits in the cargo-routing phase. Therefore, it may be profitable to consider the individual problems at the same time.

In the combined fleet-design, ship-scheduling and cargo-routing problem, all decisions explained above in the three individual problems have to be taken at the same time. The problem becomes to construct a service network and determine the routes used to transport cargo such that the profit is maximized given a certain demand matrix and cost/revenue data. The fleet design follows then directly from the allocation of ships to routes in the service network.

Thus, the objective of the overall problem is to maximize profit. Profit can be calculated by subtracting total costs from total revenue. The costs consist of:

- Capital and operating costs
- Fuel costs
- (Un)loading costs
- Transhipment costs
- Port costs

The constraints have to be formulated in such a way that feasible routes are generated, ships are allocated to the routes, the speed of the ships is determined and the cargo is allocated over the routes. Next, it will be shortly discussed what kind of constraints should be needed to obtain this.

Routes can be constructed using integer variables that indicate whether a combination of ports will be visited consecutively on a ship route or not. Then, constraints are needed that ensure that the number of consecutive ports of each port equals the number of predecessor ports of that port.

Variables can be used to allocated a ship and sailing speed for this ship to the constructed routes. Constraints will then be used that make sure that exactly one ship type and sailing speed is allocated to each route.

Finally, for the cargo allocation different constraints are needed. First of all, the flow between each pair of consecutive ports should not exceed the capacity. Next, all flow entering a port, which is not the destination port, should also leave this port. Finally, the total amount of cargo transported between two ports should not exceed the demand.

In the constraints needed to allocate the cargo over the routes, the integer variables that indicate whether two ports are visited consecutively on a route are used. However, the flow between two ports is also variable; a product of variables is needed in the cargo allocation constraints. This means that the programming formulation is not linear anymore. Methods exist to linearize the problem by adding additional (linear) constraints to the problem. Thus, using these methods a linear problem can be obtained, but the size of the problem increases. Because for the objective function and many of the other constraints also products of variables have to be linearized, it would be possible to formulate the overall problem as a mixed integer linear programming problem, but a lot of constraints will be needed. As a consequence it is not succeeded to use a column generation approach to solve the problem. Furthermore, the linear programming relaxation of the mixed integer formulation will become too large to solve in reasonable time or will lead to memory problems. Thus, although research questions 2 is answered positively, 2a and 4 have to be answered negatively. In the remaining of this thesis, the focus will be on the other research questions.

3.2 Data

To solve the combined fleet-design, ship-scheduling and cargo-routing problem, some data are needed. This section briefly describes what kind of data is needed. Later on in this thesis, the data will be discussed in more detail.

As mentioned above, the input parameters of the combined fleet-design, ship-scheduling and cargo-routing problem are a demand matrix and cost/revenue data. A distinction can be made between port data, ship data and route data. First, the port data are viewed.

- A list of ports that can be included in the ship routes.
- The sailing distance in nautical miles between the port combinations.

First of all, it has to be decided which ports are considered in the model. A (small) part of all ports in the world is thus selected and considered in the process of designing a service network. The distances between all combinations of the selected ports are also needed to determine the profitability of a service network. Distances between port combinations can relatively easily be obtained.

- Yearly demand in TEU between the port combinations.
- The revenue in $ of transporting one TEU between a port combination.

However, more port data are needed. One of the most important factors in the determination of a service network is the yearly demand between ports. However, demand is usually not known on forehand and competition makes the demand of one shipping company even more uncertain. Therefore, estimates of the demand between ports have to be made for the shipping company. Furthermore, the revenue of transporting a TEU from an origin to a destination port has to be known. Revenue can depend on many different factors, like distance to travel, size of the order, priority. Therefore, revenue per unit is also not known on forehand for each unit of freight. Furthermore, estimated demand is used, so real orders are unknown in the model. This makes it most convenient to use an estimate of the revenue per unit that only depends on the distance that has to be transported.

- A list of possible ships that can be purchased.
- The size of the ships in TEU that can be purchased.
- The feasible speeds in nautical mile per hour of the ships that can be purchased.
- The capital and operating cost in $ of the ships that can be purchased.
- The fuel cost in $ per nautical mile at a certain speed of the ships that can be purchased.

Next, some data on the available ships are needed. First, the size of the ships is important to know, because it determines the capacity. Furthermore, the possible operating speeds of each ships size are needed, because the total round tour time and thus the number of ships needed depends on the sailing speed. Ship sizes and operating speeds can usually relatively easily be obtained, so these data will probably not cause any problems. Next, the capital and operating costs to maintain a ship have to be known. Finally, the fuel cost for the different ship types and sailing speeds has to be known. The capital, operating and fuel costs are not known for all different ship sizes and/or sailing speeds. However, because they are available for some ship sizes and sailing speeds, good estimates can be made for the other needed sizes and speeds.

- The cost in $ of (un)loading one TEU in a certain port with a certain ship type.
- The cost in $ of visiting a certain port with a certain ship size.
- The time a ship stays in a port during a visit.
- The minimal buffer time that has to be allocated to a ship route

Some data depend on both the port that is visited and the ship type used on the route, like the cost of (un)loading, the cost of visiting a port and the duration of a port visit. However, in this thesis it will be assumed that they only depend on the port that is visited. Finally, the minimal amount of buffer that has to be allocated to a route has to be known. This will become one of the input parameters of the model.

3.3 Assumptions

Some assumptions have to be made to model the combined fleet-design, ship-scheduling and cargo-routing problem. In this section the assumptions are listed and explained.

3.3.1 General assumptions

- Demand between two ports is given and is assumed to be constant over time. This assumption ensures that the weekly demand between two ports can be determined from the yearly demand. This is a common assumption in researches concerning liner shipping problems.

- Demands between ports are allowed to be partly satisfied or not satisfied at all. Some demands cannot be profitable, so they can be rejected. Furthermore, it can occur that not enough capacity is available to satisfy all demand between two ports. Increasing the capacity will lead to an increase in costs that can be higher than the increase in revenue when delivering the unallocated demand. In this case it is more profitable to reject a part of the demand. Furthermore, estimates on the demand between port combinations are used, so real demand can differ. It is thus not useful to require that all demand is satisfied.

- No time restrictions are imposed on the time a cargo is on its way between its origin and destination port. Again, this assumption is imposed to simplify the model. However, the cost structure combined with the limited capacity will ensure that the distance traveled by cargo does not increase too much.

- Ships can enter and be (un)loaded at all ports. No restrictions are imposed on the size of ships. For some ports, such restrictions will hold in reality. However, the model will become too advanced when this restrictions are imposed.

- The time spent in a port depends only on the port that is visited and the type of service. This implies that the size of the ship and the number of TEU to be (un)loaded does not influence the duration of the stay in a port. However, a difference can be made in the duration of a port visit on the main routes and the duration on the feeder routes. This assumption is also made to prevent the model of becoming too complicated.

- The costs of (un)loading and visiting a port only depend on the port and not on the ship size.

- The minimum time slack between the end of a round tour and the start of a new round tour is defined for a whole round tour. The time slack is used as a buffer to capture delays. During the period between the end of a round tour and the start of a new round tour, no costs are incurred.

- Revenue per TEU depends on the direct distance between the origin and destination port of the cargo and on the direction traveled. This will be explained later.

- Each route is called once a week on a fixed day. This assumption is made in many studies on the ship-scheduling problem. In reality, shipping operators indeed visit ports on a route once a week on a fixed day. When the duration of a round tour is n days, this assumption implies that $\lceil \frac{n}{7} \rceil$ ships are needed to operate this route. ($\lceil a \rceil$ means that a is rounded to the nearest integer that is larger than or equal to a).

- There are unlimited ships of all capacities available. The fleet is built from scratch. This means that the shipping company does not own any ships at the moment and has an unlimited budget to buy new ships.

- The ships in the service networks will only be used to transport intra-regional demand. The service network will be designed without regional demand. However, when a ship has some free capacity, this can be used to satisfy regional demand. Because revenue per unit depends on the direct distance between origin and destination port, the regional demand will have significantly lower revenue than the intra-regional demand. Therefore, it will probably not be profitable to increase the ship capacity in order to transport more regional demand.

- Two different services are distinguished: main services and feeder services. Feeder services are used when demands from and to ports are first aggregated in a nearby port. The feeder services are then used to sail the demand between the port where the demand is aggregated and the nearby origin or destination port. The main services are used to sail the aggregated demand from the origin region to the destination region. Thus, large distances are served by the main service, while short distances are in general served by feeder services. In the overall solution, freights can be transhipped from feeder services to main services and vice versa.

3.3.2 Assumptions on the main services

- The order in which port clusters are visited on a route is fixed. The order will be determined on forehand and will mainly correspond to the natural order. When ports are visited in natural order, the total route distance will probably as small as possible. This excludes a lot of possible routes that are most certainly not profitable, because ports are not visited in the best order.
- Ports are allowed to be visited twice on a route, once on the eastbound trip and once on the westbound trip. This assumption can lead to asymmetric routes.
- All ships that operate on the same route have the same capacity and sailing speed. Because it is assumed that demand is constant over time, it makes also sense that ships sailing on the same routes have also equal capacities. The sailing speed depends on the route that is sailed by the ship, so on a route, each ship sails with the same speed.
- All ships can sail at all speeds considered in this thesis. In reality, large ships can probably not sail at the highest considered speeds. However, the costs for these speeds are also higher, so these speeds will probably not be selected.

3.3.3 Assumptions on the feeder services

The assumptions on the feeder services differ a bit from the assumptions on the main services. These differences are explained below.

- The sailing speed is the same for all feeder ships.
- Each port (except the central port of a cluster) is visited at most once a week by a feeder ship.
- The round tour time of a feeder route is at most one week. The only exemptions are made for direct feeder routes that cannot be served in one week.

Chapter 4

Data

This chapter describes the process of generating the data needed in the model. Lachner and Boskamp (2011) performed research on the available data in existing literature. Their objective is to find a standard data set in which general applicability and reality are combined. A data set is general applicable when it can be used in different variants of the problem. Furthermore, a data set is realistic when results obtained using the data set can be placed into perspective with the real world. They conclude that a standard data set cannot be found in the literature, so they create a new data set. Thereto, they use the service network of Maersk on the Asia-Europe trade lane. In this thesis, the port, demand and distance data as described in Lachner and Boskamp (2011) are used. Furthermore, revenue and cost data are needed in the model. The revenue data are also obtained from Lachner and Boskamp (2011). However, the data on costs they use, is not applicable to the case in this thesis, because they assume fixed speed and capacity in their model, while they can vary in this thesis. Therefore, the cost data used in this thesis are mostly obtained by Francesetti and Foschi (2002).

4.1 Ports

The ports considered in this thesis are the same as in Lachner and Boskamp (2011). The ports are obtained by merging all routes in the Asia-Europe trade lane of Maersk during spring 2010. Port Los Angeles is removed from the list, because it is not on the Asia-Europe trade lane. The 58 remaining ports, countries and regions can be found in natural order in table A.1 in appendix A.

4.2 Distance

The distances between ports can be computed using distance calculators on the internet. In Lachner and Boskamp (2011), a PHP script is used to obtain the distances between the ports. However, some values are missing because of missing ports or database errors. These missing values are then calculated using calculators on other sites. The distances can slightly differ between different calculators, but the differences are not significant. The distances between the port combinations can be found in table A.2 in appendix A.

4.3 Demand

In the allocation model it is important to know the demand between two ports. However, it is hard to achieve realistic data on the demand. In Lachner and Boskamp (2011) a method to achieve demand data using port throughput is described.

First, they select the ports that are considered by aggregating all ports used in the Asia-Europe trade lane of Maersk during spring 2010. One of the routes also includes Los Angeles, but this port is removed, because it is not on the Asia-Europe trade lane.

Thereafter, they determine total demand to be allocated on the Asia-Europe trade lane. This is done using annual reports of Maersk. Furthermore, a growth percentage is included in the calculation and corrections are made for joint services.

Finally, the total demand is divided over port combinations using port throughput. The port throughput of both the origin as the destination port is used to determine the demand of a port combination. The demand that is generated in this way can be found in table A.3 in appendix A.

4.4 Revenue

The revenue data is also obtained from Lachner and Boskamp (2011). It is assumed that the revenue per unit only depends on the distance between the origin and destination port of the demand and on the direction in which the demand has to be transported. Thereto, two revenue factors are introduced. The first factor gives the revenue of transporting one unit of cargo over one nautical mile in the westbound direction. The other revenue factor gives the revenue of transporting one unit of cargo over one nautical mile in the eastbound direction. Then, for each port combination, it is checked whether cargo has to be transported in westbound or eastbound direction. Finally, the corresponding revenue factor is multiplied with the direct distance between origin and destination port, which gives the revenue per unit of the considered port combination.

Lachner and Boskamp (2011) obtained the revenue by taking the 10-year average of historical data. This calculation gives the revenue in \$/TEU for both the eastbound and the westbound direction. Thereafter, they divided these revenues by the average distance between Asian and European ports. This results in the two revenue factors. The revenue factor is \$0.0838/nm in eastbound direction and \$0.1677 in westbound direction.

4.5 Available ships

In Francesetti and Foschi (2002) an overview of costs related to ships with different sizes is given. The ship sizes given in this article are also used in this thesis. Furthermore, some additional ship sizes are added in this study. The costs of these added ships are obtained by extrapolation on the costs given in Francesetti and Foschi (2002). The available ship sizes for both the main and feeder services can be found in tables A.4 and A.5 in appendix A. In this thesis it is assumed that an unlimited number of ships of all ship sizes are available.

4.6 Speed

From Notteboom (2006) it is learned that the speed of container vessels varies between 18 and 26 nautical miles per hour. Therefore, this range of speeds is also considered in this thesis. Furthermore, it is assumed that the speed can each time be increased by 0.5 nm per hour. Thus, seventeen different values for liner shipping vessels are considered in this thesis.

As already mentioned in chapter 3, it is assumed that feeder ships sail at a constant speed. This speed is assumed to be 22 nautical miles per hour.

4.7 Capital and operating cost

In Francesetti and Foschi (2002), the yearly capital costs are given by 10% of the purchase price of the ship. The factor of 10% is the amortization factor. The purchase prices are given for ships with different ship sizes. The purchase price of the ships considered in this thesis, that are not given in Francesetti and Foschi (2002) are determined by extrapolation.

The operating costs are defined as 5% of the purchase price of the ship plus 1.5 times the number of crew members times the average yearly wage of the crew. The crew size is multiplied by 1.5 to take illness and holidays into account. The factor 5% of the purchase price of the ship is used to take cost of maintenance, repairs, etcetera into account. On average, 18 crew members with an average yearly wage of about $\$50,000$ are present on a ship. The average yearly wage is obtained by correcting the yearly wage of Francesetti and Foschi (2002) for inflation.

An overview on the yearly capital and operating costs per ship size can be found in tables A.4 and A.5 in appendix A.

4.8 Fuel cost

The fuel consumption in ton per day is given for the different ship sizes in Francesetti and Foschi (2002) for a speed of 25 nm per hour. When this amount is divided by the distance travelled per day, the fuel consumption in ton per nautical mile is obtained. Thereafter, the fuel consumption is multiplied by the oil price in $/ton to obtain the fuel cost in $ per nautical mile for the different ship sizes. In this thesis an oil price of $500 per ton is used in the calculations.

Figure 4.1 shows the fuel consumption in ton per day for different values of the sailing speed for a ship with capacity of almost 8500 TEU. The relation between fuel consumption and sailing speed will be about the same for different ship sizes. Therefore, figure 4.1 can be

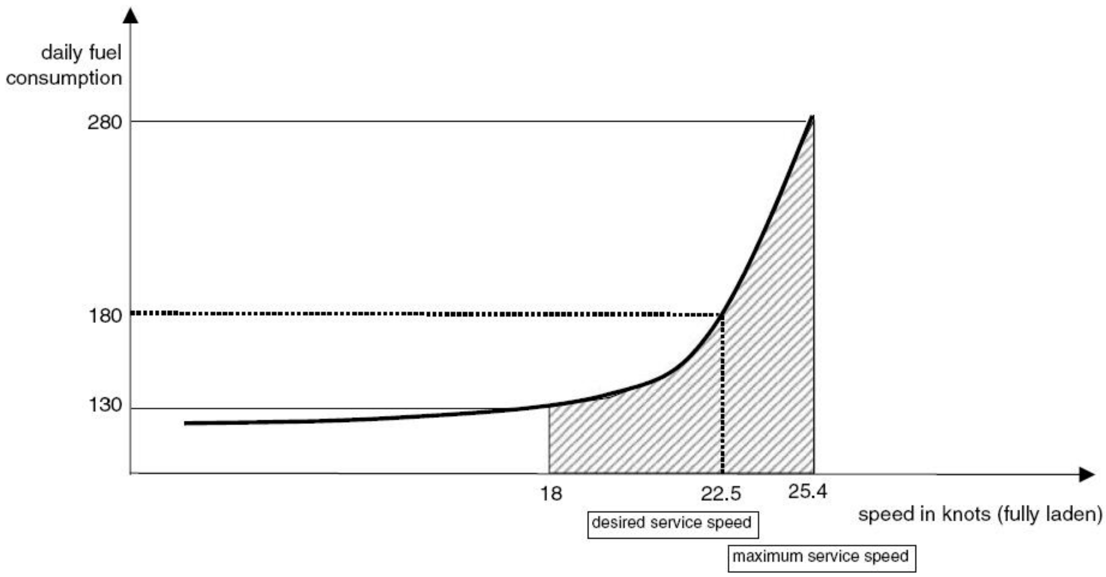

Figure 4.1: Daily fuel consumption in tpd for different sailing speeds
Source: Notteboom (2006)

used to determine factors that indicate hoe much oil is consumed at different sailing speeds. Finally, these factors can be used to determine the fuel cost in \$ per nautical mile for the other sailing speeds of the considered ships.

In table A.6 in appendix A an overview of the fuel cost for the different liner ship sizes and sailing speeds is given. The fuel costs for feeder ships are obtained in a similar way and are given in table A.5 in appendix A.

4.9 Port, (un)loading and transhipment cost

The port, (un)loading and transhipment cost are obtained from Lachner and Boskamp (2011). Port costs are incurred per port visit and usually vary between ports. Furthermore, the port costs may depend on the ship size. However, the differences in port costs are relatively small, so they are assumed to be constant per route type. In this thesis, ships are charged $\$25,000$ per port visit on a main route and $\$5,000$ per port visit on a feeder route. Thus, when a port is visited on a main route $52 \cdot \$25,000 = \$1,300,000$ is charged, because each route is performed once a week. For feeder routes, the port cost per year equals $52 \cdot \$5,000 = \$260,000$.

(Un)loading and transhipment costs are incurred per TEU (un)loaded or transhipped in a port. These costs can differ between ports and for different ship sizes. However, it is again assumed that these costs are constant per route type. The cost of (un)loading is \$175 per TEU on main routes and \$75 on feeder routes. A transhipment consist of a unloading and a loading movement, so the cost of a transhipment is $2 \cdot \$175 = \$350$ on main routes. Because each port (except the cluster centers) are only visited on one feeder route and no demand exists between ports in the same cluster, no transhipments will take place on feeder routes.

4.10 Port and buffer time

The time a ship spends in a port depends on many factors like the number of containers that have to be (un)loaded, the number of cranes available to (un)load, the arrival time, etcetera. However, these factors are uncertain, so it is difficult to determine these times. Therefore, they are assumed to be constant. The data on these times are obtained from Lachner and Boskamp (2010). In this thesis it is assumed that a ship spends 20 hour in a port on a main route and 15 hours in a port on a feeder route.

The buffer time is an additional time that is added to the route time to cover delays. The causes of delays can be divided in four groups: terminal operations, port acces, maritime passages and chance Notteboom (2006). Chance includes weather conditions and mechanical problems. In this thesis, a buffer time of at least 2 days has to be allocated to each main route. The buffer time on feeder routes is assumed to be 1 day.

Chapter 5

Cargo Allocation Model

In this chapter, a model used to solve the cargo-routing problem is presented in order to answer the following research subquestions:

1. Can one or more of the subproblems (fleet-design, ship-scheduling and cargo-routing) be formulated as a linear or mixed integer programming problem?

3. What is the performance of some known heuristics compared to the linear or mixed integer programming solution of subquestion 1?

Subquestion 1 is already answered for the fleet-design and ship-scheduling subproblems in chapter 3. For these problems it is not possible to give a linear or mixed integer programming formulation. Therefore, the only subproblem that still has to be considered in this chapter is the cargo-routing problem.

In the first section, the problem description of the model is discussed. In the next section, the model formulation is explained. Thereafter, the performance of the model is compared to the performance of heuristic algorithms to allocate cargo. Thereto, different scenarios are constructed in which the performance of the methods are compared. Next, an extension is presented and a comparison with the original model is made. In the final section of this chapter, the cargo allocation model and its extension are evaluated and the two proposed research questions are answered.

5.1 Problem description

One of the problems considered in this thesis is the determination of the optimal routing of cargo. This problem arises when the fleet-design and ship-scheduling problems are solved. Therefore, the routes are input of the problem. Furthermore, the number and size of the ships that sail the routes are known. In this thesis, the allocation over a period of one year is considered.

The yearly capacity between each pair of two consecutive ports can be calculated using the ship size of the ship that sails between those two ports and the number of times the ship sails in a year. Furthermore, it is assumed that the yearly demand between each combination of two ports is known. The cargo allocation problem can now be described as the determination of the optimal way in which the demand can be transported from their origin port to the destination port using the available routes and capacities.

When solving the cargo allocation problem, it is assumed that revenue per TEU is constant per port combination. This means that the time needed and distance covered to transport the demand from the origin port to the destination port does not influence the revenue obtained by transporting the containers. However, the distance between the origin and destination port and the direction in which the freight has to be transported influence the revenue per TEU of the port combination.

In the cargo allocation model, only costs on (un)loading and transhipping cargo are considered. All other costs, like capital, operating and fuel costs, are fixed for a given route network. Therefore, these costs are calculated afterwards.

Comparison with literature
In the literature models can be found that allocate the demand over some known routes. Next, the differences between the cargo allocation model and two such models will be discussed.

The model discussed in Song et al. (2005) can be compared with the cargo allocation model that will be used in this thesis. The major difference is that the model in Song et al. (2005) uses two objective functions. The model used in this thesis consists of only one objective function, namely the maximization of total profit. The advantage of using only one objective function is that the model is much easier to solve.

Furthermore, Álvarez (2009) describes a cargo allocation model that is comparable with the cargo allocation model discussed in this thesis. The major difference is that Álvarez (2009) uses a MIP model to allocate the demand where in this thesis an LP model is used. The integer values in the model given in Álvarez (2009) are needed to determine the number of ships needed for the routes. This decision is taken on forehand in the cargo-routing model in this thesis, such that an LP model can be used. The model in Álvarez (2009) includes costs of lost sales, which is not done in the model discussed in this thesis.

Finally, the model in Álvarez (2009) contains fuel costs. To compute fuel costs the port and sailing times have to be included in the model. In the cargo allocation model proposed in this thesis, the fuel costs are computed afterwards. This can be done because the routes are input in the model. Furthermore, in the cargo-routing model used in this thesis the costs of all routes are considered, whether they are used or not. Therefore, it is not necessarily to include the route cost in the objective function.

5.2 Model formulation

In this section the sets, parameters and variables needed to formulate the problem, will be defined. Thereafter, the objective function and constraints are formulated and explained.

5.2.1 Notation

In the cargo-routing problem the following notation is used to define the model. The sets used in the model are:

$h \in H$	set of harbours
$t \in T$	set of transhipment harbours
$s \in S$	set of ship routes
$h_1 \in p(h_2, s_1)$	set of predecessors of h_2 on ship route s_1

The following parameters are used in the model:

Rev_{h_1,h_2}	Revenue of transporting one unit from harbour h_1 to harbour h_2
$Tran_{t_1}$	Cost of a transhipment of one unit in transhipment harbour t_1
$Hand_{h_1}$	Cost of (un)loading one unit in origin or destination harbour h_1
Dem_{h_1,h_2}	Demand with origin harbour h_1 and destination harbour h_2
Cap_{h_1,h_2,s_1}	Capacity of ship route s_1 between consecutive harbours h_1 and $h_2,$ so $h_2 \in p(h_1, s_1)$
$InP_{h_1,h_2,h_3,h_4,s_1}$	0/1 parameter that takes the value 1 if a ship passes consecutive harbours h_3 and $h_4\,(h_4 \in p(h_3, s_1))$ when sailing from harbour h_1 to harbour h_2 on ship route s_1
InC_{h_1,h_2,s_1}	0/1 parameter that takes the value 1 if a ship passes both harbours h_1 and $h_2\,(h_2 \neq h_1)$ on ship route s_1

The desicion variables are:

CF_{h_1,h_2,s_1}	Flow of cargo on ship route s_1 between consecutive harbours h_1 and h_2 with $h_2 \in p(h_1, s_1)$
DF_{h_1,h_2,s_1}	Direct flow of cargo on ship route s_1 between harbours h_1 and $h_2,$ i.e. flow between two ports without using a transhipment
FTT_{h_1,t_1,h_2,s_1}	Flow of cargo on ship route s_1 between harbour h_1 and transhipment harbour t_1 with destination harbour h_2
FFT_{t_1,h_2,s_1,s_2}	Flow of cargo on ship route s_2 between transhipment harbour t_1 and destination harbour $h_2,$ where the flow to transhipment harbour t_1 was transported on ship route s_1
$FBT_{t_1,t_2,h_2,s_1,s_2}$	Flow of cargo on ship route s_2 between transhipment harbour t_1 and transhipment harbour t_2 with destination harbour $h_2,$ where the flow to transhipment harbour t_1 was transported on ship route s_1
TF_{h_1,h_2,s_1}	Total flow of cargo on ship route s_1 between harbours h_1 and h_2

5.2.2 Objective function

With the introduced notation, it is possible to show the linear programming formulation. The objective function is given by:

$$
\begin{aligned}
\max \sum_{h_1,h_2,s_1} Rev_{h_1,h_2} & \left(DF_{h_1,h_2,s_1} + \sum_{t_1} FTT_{h_1,t_1,h_2,s_1} \right) \\
& - \sum_{h_1} Hand_{h_1} \left(\sum_{t_1,h_2,s_1} [FTT_{h_1,t_1,h_2,s_1} + FTT_{h_2,t_1,h_1,s_1}] + \sum_{h_2,s_1} [DF_{h_1,h_2,s_1} + DF_{h_2,h_1,s_1}] \right) \\
& - \sum_{t_1} Tran_{t_1} \left(\sum_{t_2,h_2,s_1,s_2 \neq s_1} FBT_{t_1,t_2,h_2,s_1,s_2} + \sum_{h_2,s_1,s_2 \neq s_1} FFT_{t_1,h_2,s_1,s_2} \right)
\end{aligned}
\tag{5.1}
$$

The objective (5.1) of the cargo allocation problem is to maximize total profit. Profit is given by the revenue minus the costs. The costs consist only of (un)loading cost and transhipping cost.

The revenue is the sum of the satisfied demand of a port combination times the revenue per unit of that port combination. The revenue per unit depends on the distance between the origin and destination port and the direction of the flow. Demand that is shipped in westbound direction is more profitable than demand shipped in eastbound direction as explained in chapter 4.

The (un)loading costs are defined as the cost of loading cargo in the origin port plus the cost of unloading in the destination port. The (un)loading costs consist of the amount of cargo (un)loaded times the cost of (un)loading one unit. Transhipment flows also have to included in the determination of the (un)loading costs, because they are also loaded in their origin port and unloaded in their destination port. The additional (un)loading in a transhipment port will be included in the transhipment costs.

Finally, transhipment costs are defined as the cost of transhipping cargo from one ship route to another. They can be calculated as the product of the cost of transhipping one unit times the amount of cargo transhipped.

The capital, operating, port and fuel costs are not included in the objective function of the cargo allocation model as earlier mentioned. These costs could be included in two ways. First, for each route included in the route network, the corresponding capotal, operating, fuel and port costs can be charged, whether the route is used or not. Otherwise, these costs are only charged for routes to which cargo is allocated.

However, including the costs in the first way, will always result in the same amount of costs per route network. When these costs are included, they have to be computed in each iteration of the solving method. Thus, the computational time of the model will increase when this method is used.

When the costs are included in the second way, integer variables have to be made that indicate whether a route is used or not. However, the problem will then become a mixed integer programming problem instead of a linear programming problem. Mixed integer programming problems are harder to solve than linear programming problems, so this will also lead to an increase in computational time.

5.2.3 Constraints

The constraints of the model are:

$$\sum_{t_1,s_1} FTT_{h_1,t_1,h_2,s_1} + \sum_{s_1} DF_{h_1,h_2,s_1} \leq Dem_{h_1,h_2} \quad \forall h_1, h_2 \tag{5.2}$$

$$CF_{h_1,h_2,s_1} \leq Cap_{h_1,h_2,s_1} \quad \forall h_1, s_1, h_2 \in p\,(h_1, s_1) \tag{5.3}$$

$$\begin{aligned}\sum_{h_1} FTT_{h_1,t_1,h_2,s_1} + \sum_{t_2,s_2} FBT_{t_2,t_1,h_2,s_2,s_1} - \sum_{s_2} FFT_{t_1,h_2,s_1,s_2} \\ - \sum_{t_2,s_2} FBT_{t_1,t_2,h_2,s_1,s_2} = 0 \quad \forall t_1, h_2, s_1\end{aligned} \tag{5.4}$$

$$CF_{h_1,h_2,s_1} - \sum_{h_3,h_4,s_1} TF_{h_3,h_4,s_1} InP_{h_3,h_4,h_1,h_2,s_1} = 0 \quad \forall h_1, s_1, h_2 \in p\,(h_1) \tag{5.5}$$

$$\begin{aligned}TF_{h_1,h_2,s_1} = \sum_{h_3} FTT_{h_1,h_2,h_3,s_1} + \sum_{h_3,s_2} FBT_{h_1,h_2,h_3,s_2,s_1} \\ + \sum_{s_2} FFT_{h_1,h_2,s_2,s_1} + DF_{h_1,h_2,s_1} \quad \forall h_1, h_2, s_1\end{aligned} \tag{5.6}$$

$$CF_{h_1,h_2,s_1}, DF_{h_1,h_2,s_1} \geq 0 \quad \forall s_1, h_1, h_2 \in p\,(h_1, s_1) \tag{5.7}$$

$$FTT_{h_1,t_1,h_2,s_1} InC_{h_1,t_1,s_1} \geq 0 \quad \forall t_1, s_1, h_1, h_2 \tag{5.8}$$

$$FFT_{t_1,h_2,s_1,s_2} InC_{t_1,h_2,s_1} \geq 0 \quad \forall s_1, s_2, t_1, h_2 \tag{5.9}$$

$$FBT_{t_1,t_2,h_2,s_1,s_2} InC_{t_1,t_2,s_1} \geq 0 \quad \forall s_1, s_2, t_1, t_2, h_2 \tag{5.10}$$

Constraints 5.2 ensure that the total cargo shipped from one port to another does not exceed the demand of that port combination. Next, constraints 5.3 make sure that the total load of a ship between each two consecutive harbours does not exceed the capacity of the ship. Constraints 5.4 ensure that the flow to a transhipment port with destination port h_2 has to equal the flow from that transhipment port to the harbour h_2. In other words, they make sure that all flow unloaded to be transhipped, will also be loaded on another route. Constraints 5.5 define the the amount of flow between two consecutive ports and constraints 5.6 define the total flow between each two ports in the same cycle. Finally, constraints 5.7- 5.10 guarantee a nonnegative flow between each two ports.

5.2.4 Implementation

The model is implemented as a linear programming problem in Aimms. The parameters InC and InP need to be defined, before the model can be solved. Therefore, a procedure is created that allocates values to the parameters InC and InP. The parameter InC_{h_1,h_2,s_1} denotes whether ports h_1 and h_2 are both visited by ship s_1 or not. So, for each ship (route) it is checked which ports are visited and InC takes the value 1 for all combinations of these ports and the corresponding ship. Note that only combinations containing two different ports are considered. Next, the parameter InP has to be defined. This is a bit more complicated as $InP_{h_1,h_2,h_3,h_4,s_1}$ denotes whether consecutive harbours h_3 and h_4 are visited when sailing with ship s_1 from harbour h_1 to h_2. Note that consecutive harbours h_3 and h_4 are only visited when they are part of the shortest path between harbours h_1 and h_2 when only ship s_1 can be used. Therefore, the procedure in Aimms determines the shortest path between harbours h_1 and h_2 using only ship s_1. Thereafter, InP is allocated the value 1 to all consecutive harbours that are part of this shortest path.

5.3 Comparison with heuristics

In this section the performance of the model discussed in the previous section will be compared with the performance of some heuristics that are developed to solve the cargo allocation problem. First, the heuristics used for the comparison will be discussed. Next, some test cases are presented, whereafter the performances are compared to the model used in this thesis.

5.3.1 Heuristics

In general, heuristics are used to find a good approximation of an optimal solution in a reasonable amount of time. Heuristics are often used when finding an optimal solution for the problem is very complex or time consuming. Each heuristic has strengths and weaknesses, so when different test cases are considered, the heuristics will probably differ in performance. The value of an optimal model can be determined by comparing the solutions of the model with solutions found by heuristic methods. Three heuristics are used to determine the performance of the cargo allocation model. In the following sections, these heuristics will be presented.

5.3.1.1 KWM Algorithm

The *Ka Wang Man* (KWM) algorithm is presented in Lachner and Boskamp (2010) and is based on the heuristic algorithm used in Man (2007). The algorithm consists of two parts: in the first part, feasible routes are generated and in the second part the demand is allocated over the routes. In the comparison, only the second part of the algorithm is used.

First the order in which the demand pairs are considered is decided. The KWM algorithm considers first demand pairs with origin in Asia and destination in the Middle East and Europe. Next port combinations with origin in the Middle East and destination in Europe are considered. Thereafter demand from Europe to the Middle East and Asia is considered and finally demand from the Middle East to Asia. The order within each of these four subcategories is randomly determined.

When the order in which the demand pairs will be considered is determined, the first demand pair is selected. All direct paths between the origin and destination port of the demand pair are searched in the routes. Thereafter, the shortest paths are selected. The demand is equally allocated over these shortest paths, taking the capacity into account. When the paths have too little capacity to cover the total demand, the maximum capacity is allocated to all shortest path and the remaining demand is equally allocated to all paths that contain one additional port. This process is repeated until the total demand is allocated, or all paths are fully used. Thereafter, the next demand pair is considered and the same procedure is performed.

5.3.1.2 PDA Algorithm

The *Profit-Driven Allocation* (PDA) algorithm is also presented in Lachner and Boskamp (2010). The structure of the PDA algorithm is comparable with that of the KWM algorithm: first a starting set of routes is generated whereafter the cargo is allocated to the routes. The PDA algorithm is developed to improve the performance of the cargo allocation. The authors state that the major criticism of the KWM algorithm is that it optimizes allocation of demand in stead of optimizing revenue. Therefore, the PDA algorithm takes profit into account when selecting a route to allocate demand. Again, only the cargo allocation part of the algorithm is used for the comparison in this chapter.

Demand is allocated by iterating through the demand matrix starting in the top left corner in the PDA algorithm. However, starting in the top left corner is arbitrarily chosen and should not have a large influence on the results found by the algorithm. For each selected demand pair, all routes of the starting set are searched for a path between the origin and destination port of the demand pair. If a route contains both the origin and destination of the demand pair, it is stored.

Thereafter, the active routes are selected. A route is active when some demand is already allocated to this route. These active routes are sorted based on marginal profits. Marginal profits are defined as the difference in the additional revenue and the (un)loading cost in the origin and destination port. The load is allocated to the route with the highest profit. When this route does not have enough capacity available, the remaining cargo is allocated to the route that has the second highest profit.

This process is repeated until all load is allocated, or until the total capacity is allocated to all active routes. If there is still unallocated demand after all active routes are considered, the other routes that call both the origin and destination port are selected. These routes are sorted according to expected profits based on the selected demand pair.

Then the cargo is again allocated starting with the route associated to the highest profit and thereafter the routes descending in expected profit until either all demand is allocated or no more routes are available. Note that cargo is only allocated to an inactive route when at least a predetermined number of containers can be allocated to it, because the route would be unprofitable otherwise.

5.3.1.3 AUH Algorithm

The *Allocation Using Hubs* (AUH) algorithm is presented in Van de Weerd (2009). The main difference between the AUH algorithm and KWM and PDA algorithm is the use of hubs in the AUH algorithm. The idea is to iterate through the demand matrix and allocate the demand to routes that have enough capacity.

First, the routes that both contain the origin and destination port are selected. Then, demand is allocated to the route with the least number of ports. When a route does not have enough remaining capacity to cover all demand, the remaining capacity is used for this demand pair and the remaining demand will be allocated to the next route.

When all routes that contain both the origin and destination port of the demand pair are considered and some demand has still to be allocated, the use of hubs is considered. A hub is defined in this heuristic as a port that is part of each route and where a transhipment can take place. When all direct routes between the origin and destination port of a demand pair are considered, the demand is allocated to a route that contains the origin port and has some remaining capacity. Furthermore, the demand from the hub to the destination port is increased with the amount transported from the origin port to the hub.

When not enough capacity is available on a route to allocate all remaining demand, the next route is considered. This is repeated until all routes are considered, or all demand is allocated. Thereafter, the next demand pair is selected until all demand pairs are considered.

Finally, it has to be checked, whether all demand transported to a hub indeed is allocated to the final destination. Demand with another origin than the hub is assumed to be allocated prior to demand originated from the hub.

5.3.2 Performance measure

For each heuristic, a performance measure of the solution has to be determined. In this case, the profit of a solution is used as performance measure. The profit can be found by subtracting the costs from the revenues. The revenues between two ports are calculated by multiplying the satisfied demand between these two ports with a certain revenue per unit. The revenue per unit can be constant or dependent on the distance between the ports. When the revenues between each combination of two ports is computed, the total revenue can be found by adding all these revenues together.

Thereafter, the costs of the heuristics have to be considered. The following costs are taken into account: port costs, fleet costs, fuel costs, (off)loading costs and transhipment costs. At a first sight, the port, fleet and fuel costs seem unnecessarily; since each heuristic has the same set of routes as input, these costs would be the same. However, the heuristics do not necessarily use all routes in the input set.

When some routes are not used, the costs on those routes are also not incurred. Therefore, for each set of routes, both the costs when all routes (both the used routes as the unused routes) are considered in the cost calculation and the costs when only used routes are considered, are compared.

Port and fleet costs consist of a constant cost per port visited or per ship used. Fuel costs depend on the distance traveled and the average speed. (Un)loading costs are assumed to be included in the revenue per unit and are thus not considered separately. Finally, transhipment costs can be calculated by multiplying a constant cost by the number of transhipped containers.

5.3.3 Test cases

In this section the test cases used for comparison will be discussed. The test cases differ from the data given in chapter 4. Some input parameters will be constant in each test case, for example the average speed, the different costs per unit except the transhipment cost per unit, the origin destination demand and the distance matrix. Other input data will be variable, these are: number of ports, number of routes in starting set, profit per unit and transhipment cost per unit. For each of the variable inputs, some options are defined. Then, a basic case is constructed where for each of the variables one option is chosen. The other cases can now be obtained by changing one variable compared to the basic case.

Each case needs a starting set of routes as input. The routes can be chosen in two ways. The first possibility is to generate routes at random from all possible routes. The other possibility is to randomly generate routes from all possible routes containing a certain hub. In the comparison, both methods of generating routes are used, where the hub in the second method is chosen at random. The performance of these two ways to obtain a starting set of routes is compared, because the AUH algorithm is the only heuristic approach that makes use of hubs.

The remaining of this section will be used to present the data used to generate the test cases. Most data are originally used in Man (2007). Furthermore, the parameter settings of the basic case are given.

In the test cases a maximum of nine ports are considered. Table 5.1 gives an overview of these nine ports. The table provides information about the port name, the abbreviation used in this comparison and the region in which the port is situated. The region is important when using the KWM algorithm. The distances between two ports are shown in table 5.2. The distance are given in nautical miles. Table 5.3 shows the origin-destination demand between ports in 1000 TEU per year.

In table 5.4 the parameter settings of the test cases are presented. The fixed parameters take the same value in each test case. In the middle of the table, the value taken by the variable parameters in the basic case are shown. Finally, the other possible values of the variable parameters are given. The test cases can be obtained by changing one value of a variable parameter from the basic case by one of the other possible values for that parameter. In this way, two test cases with different number of ports, one test case with different revenue, three test cases with different number of routes and two test cases with different transhipment cost can be distinguished besides the basic case. This makes the total number of test cases equal to nine.

As explained earlier, the costs can be computed in two ways. First, all routes can be considered in the cost calculation. The second way is to consider only the used routes in the cost

Table 5.1: Port names and characteristics

Port name	Abbreviation	Region
Tokyo	TO	Asia
Shanghai	SH	Asia
Hong Kong	HK	Asia
Singapore	SI	Asia
Jebel Ali	JA	Middle East
Port Said	PS	Middle East
Antwerp	AN	Europe
Rotterdam	RO	Europe
Hamburg	HA	Europe

Table 5.2: Distances between ports in nautical miles

O/D	TO	SH	HK	SI	JA	PS	AN	RO	HA
TO	0	1048	1596	2904	6353	7914	11191	10966	11439
SH	1048	0	845	2237	5686	7247	10524	10519	10772
HK	1596	845	0	1460	4909	6470	9747	9742	9995
SI	2904	2237	1460	0	3449	5016	8293	8068	8541
JA	6353	5686	4909	3449	0	2908	6187	6182	6435
PS	7914	7247	6470	5016	2908	0	3279	3274	3527
AN	11191	10524	9747	8293	6187	3279	0	149	405
RO	10966	10519	9742	8068	6182	3274	149	0	305
HA	11439	10772	9995	8541	6435	3527	405	305	0

Table 5.3: Demand between origin and destination port in 1000 TEU per year

O/D	TO	SH	HK	SI	JA	PS	AN	RO	HA
TO	0	0	0	87	23	11	100	223	138
SH	0	0	0	92	18	16	151	631	364
HK	0	0	0	80	20	14	116	312	185
SI	118	131	75	0	24	10	149	358	277
JA	42	28	36	21	0	0	46	51	39
PS	34	45	24	18	0	0	38	40	24
AN	102	132	113	72	0	10	0	0	0
RO	110	501	175	155	8	13	0	0	0
HA	98	280	164	123	3	12	0	0	0

Table 5.4: Parameter settings test cases

Fixed parameters	
Average speed in knots	26
Ship size in TEU	10,000
Capital and operating cost per ship per year in $	18,000,000
Fuel cost per nautical mile in $	100
Port cost in $	200,000
Time spent in port in hours	20
Minimum slack time per route in hours	2
Minimum route length	4
PDA minimum allocation demand in TEU	250,000

Variable parameters basic case	
Number of ports	7
Ports used	TO,SH,SI,JA,AN,RO,HA
Revenue per unit per nautical mile	50
Number of routes	7
Transhipment cost in $	200

Variable parameters other cases	
Number of ports	5,9
Ports used (in case of 5 ports)	TO,SH,SI,AN,RO
Revenue per unit	500
Number of routes	3,5,10
Transhipment cost in $	0,400

calculation. Furthermore, routes can be generated in two different ways. The generation of the routes can be totally at random, or at random from a set of all routes containing a certain hub. Thus, each test case can be performed in four different ways. In this thesis, those four possible ways are denoted as:

- no hubs, all routes (NH,AR);
- no hubs, only used routes (NH,OR);
- hubs, all routes (H,AR);
- hubs, only used routes (H,OR).

Here, hubs denote that the routes are generated from a set of routes containing a certain hub. No hubs indicate that routes are generated at random. Furthermore, all routes means that the costs of all routes are considered in the cost calculation, where only used routes denotes that only the costs of routes that are indeed used are considered. Remember that the costs of the routes are not included in the objective function of the CAM model, but are calculated afterwards, because it is assumed in the CAM model that costs of all routes are incurred independently of whether they are used or not. However, because some of the heuristics may perform better when only costs of used routes are incurred, this scenario is also considered in the comparison. In this case, the costs of the routes are still calculated afterwards for the CAM model. However, now only costs of used routes are subtracted from the profit.

The results will be compared using four scenarios. In a scenario three of the four variable input parameters are fixed at the basic value. All test cases where those three parameters take the basic value are included in the scenario. Note that the basic test case is included in all scenarios. The four scenarios have variable number of ports, revenue per unit, number of routes and transhipment cost. The relative performance of the heuristics with respect to the optimal model of the test cases within a scenario can be compared.

5.3.4 Results

In this section, the results of the comparison will be discussed. First, the performance of the heuristics with the basic parameter settings will be given. Thereafter, the results of the four scenarios will be discussed.

5.3.4.1 Basic case

First, the results of the basic case will be discussed. The basic case can be distinguished in four separate scenarios as discussed earlier. For each of these four scenarios, a comparison between the performance of the heuristics can be made. Furthermore, for each heuristic, it can be determined in which scenario the best performance is obtained. Therefore, in this section, the results will be discussed per scenario, so a comparison between heuristics for the same scenario can be made. Thereafter, the performance of the heuristics in scenarios with hubs will be compared with the performance in scenarios without hubs. Finally, the same is done for scenarios in which all routes are used in the cost calculation versus scenarios in which only the costs of the used routes are considered.

Now, the definition of some characteristics used in the comparison will be discussed. As described earlier in this thesis, profit will be the performance measure for the methods. Both absolute and relative profits will be compared. Relative profits can be defined in different ways, where two decisions have to be made.

First, a standard method has to be chosen to which relative profits can be defined (this decision concerns the denominator in the calculation). For example, when the relative profit of the AUH algorithm with respect to the KWM algorithm is determined, the KWM algorithm is the standard method. In the comparison, four methods are compared. Three of these methods are heuristics, the fourth is an optimal model. It seems reasonable to choose the optimal model (CAM) as standard method. An advantage of using the optimal model as standard method is that the relative profits of the different heuristics can be compared with each other, because they are all divided by the same profit.

The second decision concerns the definition of the nominator. The nominator can be defined as the absolute profit of the heuristic method or as the absolute difference in profits between the heuristic method and the optimal method. For the comparison, it does not matter which of the two options is chosen. In this thesis, the nominator is defined as the absolute value of the profit of the heuristic method minus the profit of the optimal model.

The relative difference in profits are thus considered. A negative value represents a lower profit than the profit of the cargo allocation model. When the value is 0, the profit of the heuristic and the cargo allocation model are equal and a positive value indicates that the heuristic has a higher profit than the cargo allocation model.

Each case will be performed with 50 different route sets as input. For all these 50 results, the relative difference in profit between the heuristics and the optimal model will be calculated. Thereafter, the average relative difference is found by taking the average of the relative differences of the 50 results. Finally, a 95% confidence interval for the relative difference in profit is constructed. The bounds of the 95% confidence interval are obtained by taking the 2.5 and 97.5 percentiles from the 50 results.

The results of the four cases will now be presented. For each case, a comparison between the (optimal) CAM model and the three heuristic algorithms will be made.

No hubs, all routes
In table 5.5 the results are given of the test case in which the costs of all routes are considered and routes are generated at random. The different characteristics are shown for the three heuristics and the (optimal) cargo allocation model (CAM). The profit, revenue and all costs, except the transhipment costs, which are given in millions of $, are given in billions of $. Finally, the demand fulfilled (given in million TEU) and the percentage of demand fulfilled with respect to the total demand are shown.

It can be seen from table 5.5 that the AUH algorithm has on average the best performance of the heuristics. With the heuristic methods as only concern, the average profit, revenue and demand fulfilled are all the highest for the AUH algorithm. Furthermore, the AUH is on average the fastest method to solve the problem.

The average costs of the AUH algorithm are slightly higher than the costs of the other two heuristics. The reason for this is that the port, fleet and fuel costs are the same for all methods, because the costs of all routes in the route set are considered. The route sets are the same for all methods, so the costs are also the same. The AUH algorithm is the only heuristic method that is able to allocate demand using a transhipment action. Therefore, some additional costs are related to the AUH algorithm.

The performance of the KWM algorithm is on average lower than the performance of the AUH heuristic. However, the average profit is still positive unlike the average profit of the PDA algorithm. Thus, the PDA algorithm gives on average a loss, where the other two heuristics give profits. This is caused by the much lower average revenue and demand fulfilled of the PDA algorithm compared to the other heuristic methods. Finally, the average computational time is about two times higher for the PDA algorithm than for the other heuristics.

As expected, the average profit of the (optimal) cargo allocation model is higher than the profits of all three heuristics. The same holds for the average revenue and demand fulfilled. The average costs are slightly higher than that of the KWM and PDA algorithm. The reason for this is explained earlier: in the CAM it is also possible to tranship loads from one ship to another. The average computational time of the CAM is higher than that of the heuristics. However, the increase in performance is in this case more important than the increase in computational time, because the computational is still less than a second.

Table 5.6 gives information on the relative difference of the profit between the heuristics and

Table 5.5: Results of the basic case (NH,AR)

	KWM	PDA	AUH	CAM
Profit in billion $	0.541	-0.522	0.885	1.173
Revenue in billion $	2.763	1.700	3.116	3.395
Costs in billion $	2.221	2.221	2.232	2.222
Demand fulfilled in million TEU	3.864	2.117	4.253	4.657
Percentage demand fulfilled	82.3	45.1	90.6	99.2
Port costs in billion $	0.469	0.469	0.469	0.469
Fleet costs in billion $	0.883	0.883	0.883	0.883
Fuel costs in billion $	0.868	0.868	0.868	0.868
Transhipment costs in million $	0	0	10.108	0.492
Computational time in seconds	0.087	0.155	0.076	0.711

the optimal model (CAM). In the table, the average relative difference and the bounds of the 95% confidence interval are shown for each of the three heuristics. Because the cargo allocation model is optimal, the relative differences should all be less than or equal to 0. This can indeed be seen in the table. Again, it can be seen that the PDA algorithm performs worse than all other methods. The 95% confidence interval of this method lies completely under the confidence intervals of the other two methods. The method performs always more than 100% worse than the optimal model, which means that the PDA algorithm will always lead to a loss in this case.

The difference between the KWM and AUH algorithm is much smaller. The 95% confidence intervals have about the same width, and largely overlay each other. The performance of the AUH algorithm is a bit better. The upper bound of the confidence interval equals 0, which means that in at least 2.5% of the time, the profit of the AUH algorithm equals the profit of the optimal model.

Table 5.6: 95% confidence intervals for the basic case (NH,AR)

	LB	Mean	UB
KWM	-1.511	-0.575	-0.073
PDA	-3.237	-1.550	-1.137
AUH	-1.400	-0.283	0.000

No hubs, only used routes

Table 5.7 shows the results of the case in which only the costs of used routes are considered and routes are generated at random. The optimality of the CAM model cannot be guaranteed anymore in this case. The reason for this is that the route-dependent costs (port costs, fleet costs and fuel costs) are not included in the objective function of the model. They are calculated afterwards, because the model will become integer when including them in the objective function, which will lead to longer computational times. Therefore, the CAM model does not necessarily choose the optimal routes to use. Nevertheless, the average profit of the CAM model is higher than the average profit of the heuristics.

The AUH algorithm has the highest average profit of the three heuristics, followed by the KWM and PDA algorithms. However, in this case, the PDA algorithm does not incur on average a loss anymore. Furthermore, the average profit of the PDA algorithm is only a bit lower than that of the KWM algorithm. The order of the average revenue and demand fulfilled is the same as the order of the average profit. The PDA algorithm satisfies the least demand and thus incurs the least profit. However, the average costs are also lower than that of the other models. Apparently, the PDA algorithm uses less routes and/or routes that have lower costs than the routes used by the other algorithms.

The highest costs are incurred by the KWM algorithm, while both the AUH algorithm and the CAM model deliver more load than the KWM algorithm. Furthermore, both in the AUH algorithm and CAM model are transhipment movements possible, which will lead to transhipment costs, while these movements are not possible in the KWM algorithm. The AUH algorithm and CAM model apparently chose better cost-effective routes than the KWM algorithm.

The CAM model is on average better in choosing cost-effective routes than the AUH algorithm, which can be seen by the lower costs and higher revenues and demand fulfilled. However, the computational time of the CAM model is higher than that of the heuristics, so a trade-off between computational time and profit has to be made. Again, the increase in profit will probably be more important than the increase in computational time, because the computational time is still reasonable.

Table 5.7: Results of the basic case ((NH,OR)

	KWM	PDA	AUH	CAM
Profit in billion $	0.541	0.458	0.941	1.369
Revenue in billion $	2.763	1.700	3.116	3.395
Costs in billion $	2.221	1.241	2.175	2.026
Demand fulfilled in million TEU	3.864	2.117	4.253	4.657
Percentage demand fulfilled	82.3	45.1	90.6	99.2
Port costs in billion $	0.469	0.274	0.456	0.432
Fleet costs in billion $	0.883	0.489	0.861	0.804
Fuel costs in billion $	0.868	0.479	0.848	0.789
Transhipment costs in million $	0	0	10.108	0.492
Computational time in seconds	0.093	0.165	0.077	0.671

Table 5.8 gives the mean and 95% confidence intervals of the relative difference of the profit between the heuristics and the cargo allocation model. Now, the relative differences are not necessarily smaller than or equal to 0, because the performance of the cargo allocation model is not guaranteed to be optimal. The upper bound of the AUH algorithm is indeed slightly higher than 0, which means that in at least 2.5% of the cases, the AUH heuristic performs better than the CAM model. The upper bounds of the PDA and KWM algorithms are smaller than 0, which means that these heuristics can perform better than the CAM model in at most 2.5% of the cases. However, this number will in practice be a lot lower, because the 97.5 percentile is still relatively far from 0.

From the table, it can be concluded that the performance of the PDA algorithm is the most constant compared to the CAM model. This can be seen by the width of the 95% confidence interval. Despite the lowest average profit and upper bound of the PDA algorithm, it can be argued that the PDA algorithm performs better than the KWM algorithm, because the

Table 5.8: 95% confidence intervals for the basic case (NH,OR)

	LB	Mean	UB
KWM	-1.208	-0.606	-0.143
PDA	-0.941	-0.661	-0.428
AUH	-0.980	-0.307	0.002

KWM algorithm has more negative outliers. Furthermore, the lower bound of the KWM algorithm is smaller than -1, which means that in at least 2.5% of the cases a loss is incurred by the KWM algorithm. The AUH algorithm performs best of the heuristics, because both the 95% confidence of the relative difference compared to the CAM model and the mean are nearest to 0. The lower bound of the AUH algorithm is slightly lower than that of the PDA algorithm, so the AUH algorithm has bigger outliers. However, the difference in mean and upper bound is larger between these two heuristics, so the AUH algorithm is preferred in this case.

Hubs, all routes

Table 5.9 shows the results of the case in which the costs of all routes are considered and routes that contain a hub are generated. As expected, the cargo allocation model has again the best average performance. Besides, the order in performance of the heuristic is the same as in case with randomly generated routes. The highest average profit, revenue and demand delivered are obtained by the AUH algorithm, followed by the KWM and PDA algorithms, where the PDA algorithm again incurs a loss instead of a profit. The average transhipment costs of the AUH algorithm are much higher than that of the CAM model, which means that the hubs are more frequently used by the AUH algorithm than by the CAM model.

The average computational time is again lowest for the AUH algorithm. The CAM model takes on average about ten times as long as the AUH algorithm. The trade-off between computational time and performance is already discussed in the previous two cases.

Table 5.9: Results of the basic case (H,AR)

	KWM	PDA	AUH	CAM
Profit in billion $	0.489	-0.514	0.850	1.147
Revenue in billion $	2.753	1.751	3.158	3.412
Costs in billion $	2.265	2.265	2.308	2.266
Demand fulfilled in million TEU	3.837	2.177	4.214	4.685
Percentage demand fulfilled	81.7	46.4	89.7	99.8
Port costs in billion $	0.494	0.494	0.494	0.494
Fleet costs in billion $	0.894	0.894	0.894	0.894
Fuel costs in billion $	0.876	0.876	0.876	0.876
Transhipment costs in million $	0	0	43.224	0.976
Average computational time in seconds	0.086	0.154	0.077	0.766

As can be seen in table 5.10, the 95% confidence interval of the KWM algorithm is very wide, which means that the KWM algorithm gives a lot of large negative outliers. From the table it can also be concluded that the PDA algorithm has the worst performance in this case.

Table 5.10: 95% confidence intervals for the basic case (H,AR)

	LB	Mean	UB
KWM	-1.578	-0.585	-0.106
PDA	-1.857	-1.462	-1.162
AUH	-0.973	-0.260	0.000

The mean relative difference in profit compared to the CAM model is for the PDA algorithm much lower than for the other two heuristics. Nevertheless, the relative performance compared to the optimal model is quite constant, which can be seen from the small 95% confidence interval. However, 95% confidence intervals of the AUH heuristic is situated closer to 0 and the whole interval is above -1, which means that the performance of the AUH algorithm is a better approximation of the optimal performance than that of the PDA algorithm. Furthermore, the 97.5 percentile of the AUH algorithm is even equal to 0, which means that in at least 2.5% of the cases, the AUH algorithm provides the optimal solution.

Hubs, only used routes

Table 5.11 shows the results of the last case, namely the case in which only costs of used routes are considered and routes containing a hub are generated. Again, the average profit, revenue and demand fulfilled are highest for the CAM model, followed by the AUH, KWM and PDA algorithm respectively. Now, the port, fleet and fuel costs are not constant over the models, because only costs incurred on used routes are considered. It can be seen that the PDA algorithm uses the least or most cost-effective routes. The main idea of the PDA algorithm is indeed to use only cost-effective routes, so this could have been expected. Furthermore, the PDA algorithm allocates the least demand, so less capacity is needed to transport the loads and thus less costs have to be incurred.

Remarkably, the CAM model, which allocates on average the most demand, has the second-lowest costs. However, the costs of the routes are not considered when allocating the demand, so the model is not able to choose the most cost-effective routes. Nevertheless, the CAM model chooses better cost-effective routes than the KWM and AUH algorithms. The average computational times are about the same as those in the other cases.

Table 5.11: Results of the basic case (H,OR)

	KWM	PDA	AUH	CAM
Profit in billion $	0.490	0.438	0.909	1.340
Revenue in billion $	2.753	1.751	3.158	3.412
Costs in billion $	2.264	1.312	2.249	2.072
Demand fulfilled in million TEU	3.837	2.177	4.214	4.685
Percentage demand fulfilled	81.7	46.4	89.7	99.8
Port costs in billion $	0.494	0.298	0.482	0.456
Fleet costs in billion $	0.894	0.514	0.871	0.816
Fuel costs in billion $	0.876	0.500	0.853	0.799
Transhipment costs in million $	0	0	43.224	0.976
Average computational time in seconds	0.089	0.154	0.078	0.737

The relative differences in performance of the heuristics compared to the CAM model, are shown in table 5.12. Again, the 95% confidence interval of the PDA algorithm is smaller than the intervals of the other algorithms. However, the mean difference of the PDA algorithm is much higher compared to that of the AUH algorithm. The KWM algorithm has a quite large 95% confidence interval, which can denote large outliers in the cases. The AUH algorithm on the other hand, has the lowest average difference in profit and a relatively small 95% confidence interval. It can thus be concluded that the AUH algorithm performs best of the heuristics.

Table 5.12: 95% confidence intervals for the basic case (H,OR)

	LB	Mean	UB
KWM	-1.397	-0.624	-0.106
PDA	-1.000	-0.668	-0.354
AUH	-0.816	-0.313	0.045

Evaluation

In all of the above described cases, the models are ranked according to profit. Now, it can be concluded that the CAM model has the best performance in all four cases. Furthermore, in all four cases, the AUH algorithm outperforms the other two heuristics. The order of the KWM and PDA algorithm depends on which routes are included in the cost calculation.

Thus, the difference between the heuristics depend on the case; the order of the heuristics can change in different cases. Therefore, the results in different cases will be compared to each other. Two comparisons can be distinguished, namely cases in which routes are generated containing a hub versus cases in which routes are randomly generated and cases in which costs of all routes are considered versus cases in which only costs of used routes are considered.

In table 5.13 respectively the 2.5 percentile, the average and the 97.5 percentile values of the relative difference in profit of the heuristics compared to the cargo optimization model are again given between brackets. The table consists of four blocks, each block represents one of the four cases. The first column represents the cases in which the cost of all routes are considered, where the second column denotes the cases in which only costs of used routes are considered. The first three rows correspond to the cases where the routes are generated at random and the last three rows to the cases where routes including a hub are generated. Thus, the first block represents the case in which routes are generated at random and all routes are used in the cost calculation.

Table 5.13: 95% confidence intervals for the basic case

		All routes	Only used Routes
No Hubs	KWM	(-1.511,-0.575,-0.073)	(-1.208,-0.606,-0.143)
	PDA	(-3.237,-1.550,-1.137)	(-0.941,-0.661,-0.428)
	AUH	(-1.400,-0.283,0.000)	(-0.980,-0.307,0.002)
Hubs	KWM	(-1.578,-0.585,-0.106)	(-1.397,-0.624,-0.106)
	PDA	(-1.857,-1.462,-1.162)	(-1.000,-0.668,-0.354)
	AUH	(-0.973,-0.260,0.000)	(-0.816,-0.313,0.045)

Hubs versus no hubs

Table 5.13 can be used to compare the cases in which routes are generated at random with the cases in which hubs are included in the routes. The results of cases in which a hub is used in the route generation can be compared with the results of the cases in which routes are generated at random by comparing the values between brackets of the heuristics in the first three rows with that of the values in the last three rows.

For the KWM algorithm, it can be seen that all the values between brackets are slightly closer to 0 in case of randomly generated routes. Furthermore, the 95% confidence interval is a bit smaller in case of randomly generated routes. It can be concluded that the KWM algorithm performs slightly better compared to the cargo allocation model in cases where routes are generated at random than in cases where routes are generated including a hub. However, the differences are very small. This can be explained by the fact that in the CAM model transhipment movements can take place, while this is not possible in the KWM algorithm. When hubs are included in the routes, more possible transhipment movements are possible, so the CAM model will be more advantageous than the KWM algorithm in this cases.

For the AUH algorithm, the average relative performance and upper bound are about the same in both cases. However, the lower bound is closer to 0 in cases where hubs are included in the routes. Thus, the AUH algorithm has less negative outliers when hubs are included in the routes than when routes are generated at random. The AUH algorithm is developed to solve problems where hubs are included in the routes, so this could have been expected.

Finally, the performance of the PDA algorithm compared to the cargo allocation model improves when hubs are included in the routes. The average profit lies a bit closer to 0 when hubs are included in the routes. Furthermore, the 2.5 percentile value becomes much closer to 0 in case all routes are included in the cost calculation, which results in a smaller 95% confidence interval. Thus, when all routes are considered in the cost calculation, less negative outliers are observed for the PDA algorithm when hubs are included in the routes than when routes are generated at random. When only costs of used routes are considered, more outliers, both positive and negative, are obtained using the PDA algorithm when hubs are included in the routes. On forehand, it was not expected that the performance of the PDA algorithm would increase when routes including hubs are generated. In the PDA algorithm, unlike in the CAM model, loads cannot be transhipped. Therefore, it was expected that the improvement of the CAM model should be greater than the improvement of the PDA algorithm after including hubs.

All routes versus only used routes
The comparison between cases in which all routes are used in the cost calculation and cases in which only the cost of used routes are included can also be made using table 5.13. Now, the cases can be compared by comparing the values between brackets in the first column (all routes) with those in the second column (only used routes).

First of all, the average performance of the KWM algorithm compared to the CAM model decreases when only costs of used routes are incurred. However, the 2.5 percentile value become closer to 0, so less negative outliers are incurred when only used routes are included in the cost calculation. Both the KWM algorithm and the CAM model are not able to select the most cost-efficient routes to use. However, the cargo allocation model uses as little routes as possible to satisfy the optimal number of demand. Therefore, the CAM model selects apparently routes which have in total less costs than the KWM algorithm.

The AUH algorithm shows a decrease in average relative profit compared to the CAM model when only used routes are considered. On the other hand, both the 2.5 and 97.5 percentile value increase in this case. The 95% confidence interval becomes smaller when only used routes are considered, which means that there are less outliers in profit with respect to the CAM model. In general it can be concluded that the CAM model selects on average better cost-efficient routes than the AUH algorithm, while the AUH algorithm has less outliers. The explanation for this can again be found in the minimization of the number of routes in the cargo allocation model, which results in lower total costs of used routes.

Finally, the performance of the PDA algorithm with respect to the CAM model can be compared for both situations. The PDA algorithm uses in general very little routes compared to the other heuristics and the optimal CAM model. Therefore, it is expected that the performance of the PDA heuristic compared to the cargo allocation model will increase when only costs of used routes are incurred in stead of costs of all routes. From table 5.13 it can indeed be seen that the performance of the PDA algorithm improves when only used routes are included in the cost calculation. All values between brackets (2.5 percentile, mean and 97.5 percentile) become closer to 0 when only used routes are considered. Furthermore, the 95% confidence interval becomes smaller, which means that there are less outliers in performance compared to the CAM model. Furthermore, it can be seen that the confidence intervals lie under -1 when all routes are considered and above -1 when only used routes are considered. This means, that in at most 2.5% of the cases in which all routes are considered a profit is obtained using the PDA algorithm, while in at most 2.5% of the cases in which only used routes are considered a loss in incurred.

Conclusion
It can be concluded that the AUH algorithm has in general the best performance of the heuristics in the basic case. The order of the other two heuristics depends on the case.

The KWM algorithm shows the most constant performance compared to the optimal cargo allocation model. The results do not differ much between cases in which routes are generated at random or including a hub and in cases in which costs of all routes or only used routes are incurred.

The performances of the AUH and PDA algorithms with respect to the CAM model are dependent on the case that is used. The AUH algorithm performs on average better in cases where costs of all routes are incurred. However, the AUH algorithm has also more outliers in this case. When hubs are included in the routes, the average performance does not change, but again the number of outliers decrease. The PDA algorithm, on the other hand, performs best in cases where only costs of used routes are included in the cost calculation.

In general, the AUH heuristic has the best performance of the heuristics. Dependent on the difference in average computational time, a choice between the AUH heuristic and optimal CAM model has to be made. For the basic case, the average computational time of the CAM model is less than a second, so the optimal CAM model is preferred.

5.3.4.2 Scenario 1: Variable number of ports

In this section the influence of the number of ports on the performance of the heuristics is investigated. In table 5.14 the average profit of the heuristics and the optimal model are given for different number of ports. The table distinguishes between the four cases discussed in the previous sections. Again, the AUH algorithm outperforms the other two heuristics on average. The order of the other two heuristics depend on the case.

Table 5.14: Average profit in billion $ for the scenario with variable number of ports

No hubs, all routes	KWM	PDA	AUH	CAM
5 ports	0.130	-0.831	0.237	0.307
7 ports	0.541	-0.522	0.885	1.173
9 ports	0.792	-0.539	1.321	2.017

No hubs, only used routes	KWM	PDA	AUH	CAM
5 ports	0.130	0.497	0.510	0.955
7 ports	0.541	0.458	0.941	1.369
9 ports	0.792	0.298	1.321	2.017

Hubs, all routes	KWM	PDA	AUH	CAM
5 ports	0.065	-0.910	0.167	0.245
7 ports	0.489	-0.514	0.850	1.147
9 ports	0.773	-0.564	1.014	1.958

Hubs, only used routes	KWM	PDA	AUH	CAM
5 ports	0.065	0.506	0.572	0.969
7 ports	0.490	0.438	0.909	1.340
9 ports	0.773	0.282	1.021	1.958

However, it is hard to compare the cases with different number of ports using only average profit, because the performance of all three heuristics and the optimal model differ for a different number of ports. Therefore, the mean relative difference in average performance between the heuristics and the optimal model are given in table 5.15. The relative difference in average profit between the CAM model and itself is logically 0 and is not shown in the table. However, because it is 0 for all number of ports, it can be used as reference. Now, the values of the heuristics in the cases with different number of ports can be compared to each other.

From the table, it can be seen that the KWM and AUH algorithm performs on average best when seven ports are included in the case. When the number of ports is increased or decreased the average performance decreases. For both methods one case is an exemption, but the differences are small in these cases. The PDA algorithm performs better when less ports are included in cases where only used routes are included in the cost calculation, while it performs better when more ports are included in cases where costs of all routes are incurred. This can probably be explained by the difference in allocation method of the PDA algorithm compared to the other models. The PDA algorithm uses only new routes when the route is considered to be profitable. In practice, the PDA algorithm uses very little routes compared to the other models. In cases of only five ports, it is less likely that routes are considered as profitable, so less routes are used. Therefore, the revenues will be very low compared to the other methods in which (almost) all demand can be satisfied. In cases where all routes are

Table 5.15: Mean relative difference in average profit of the scenario with variable number of ports

No hubs, all routes	KWM	PDA	AUH
5 ports	-0.578	-3.703	-0.229
7 ports	-0.539	-1.445	-0.246
9 ports	-0.607	-1.267	-0.345

No hubs, only used routes	KWM	PDA	AUH
5 ports	-0.864	-0.479	-0.466
7 ports	-0.604	-0.665	-0.313
9 ports	-0.607	-0.852	-0.345

Hubs, all routes	KWM	PDA	AUH
5 ports	-0.734	-4.719	-0.316
7 ports	-0.574	-1.448	-0.259
9 ports	-0.605	-1.288	-0.482

Hubs, only used routes	KWM	PDA	AUH
5 ports	-0.933	-0.478	-0.409
7 ports	-0.634	-0.673	-0.321
9 ports	-0.605	-0.856	-0.479

incurred in the cost calculation, the costs are then very high compared to the revenue, which leads to low profits/high losses. However, when only costs of used routes are considered, the costs are also very low, which can lead to higher profits.

When different number of ports are considered, the computational time of the methods also becomes important, because the problem size increases. Therefore, in table 5.16 the average computational times of the four methods are given when the model is solved with different number of ports. In the table, no distinction is made between cases with or without hubs and cases in which costs of all routes or only used routes are included, because the average computational times in these different cases hardly differ. From the table, it can be seen that the computational time of the AUH heuristic hardly increases when the number of ports increases. On the other hand, the computational times of the other two heuristics and the optimal CAM model increases with the number of ports. The increase in computational times is highest for the optimal CAM model, but the average time needed to solve an instance with 9 ports is still reasonable for the CAM model.

Table 5.16: Average computational times for the scenario with variable number of ports

	KWM	PDA	AUH	CAM
5 ports	0.047	0.071	0.076	0.279
7 ports	0.088	0.158	0.077	0.726
9 ports	0.138	0.260	0.079	1.652

In general, it can be concluded that the heuristics can best be used when the number of ports considered is mediate. However, one could have been expected that heuristical methods perform better when less ports are included, because the performance of heuristics decreases in general when the problem size increases. When the number of ports is increased, the CAM model gives significant better results, but the computational time also increases. However, the average time needed to solve the instances is still reasonable, so the CAM model is preferred in these cases.

5.3.4.3 Scenario 2: Variable revenue per unit

The second scenario that is considered is the scenario with variable revenue per unit. Table 5.17 shows the average profit in cases with constant revenue per unit and in cases with distance dependent revenue per unit. Again, the AUH algorithm outperforms the other two heuristics on average in all cases.

Table 5.17: Average profit in billion $ for the scenario with variable revenue per unit

No hubs, all routes	KWM	PDA	AUH	CAM
Constant revenue	0.402	-0.506	0.567	0.785
Distance dependent revenue	0.541	-0.522	0.885	1.173
No hubs, only used routes	**KWM**	**PDA**	**AUH**	**CAM**
Constant revenue	0.402	0.192	0.628	0.897
Distance dependent revenue	0.541	0.458	0.941	1.369
Hubs, all routes	**KWM**	**PDA**	**AUH**	**CAM**
Constant revenue	0.345	-0.517	0.524	0.765
Distance dependent revenue	0.489	-0.514	0.850	1.147
Hubs, only used routes	**KWM**	**PDA**	**AUH**	**CAM**
Constant revenue	0.345	0.142	0.558	0.896
Distance dependent revenue	0.490	0.438	0.909	1.340

To compare the situations with constant profit per unit with situations in which the profit depends on the distance between the origin and destination port, table 5.18 is used. In this table, the mean of the relative difference in average profit of the heuristics with respect to the optimal CAM model is shown. The closer the mean is to 0, the better is the performance.

The heuristics show the same structure in all cases. Independent on the inclusion of hubs and the way the costs are calculated, the KWM algorithm performs better in the cases in which a constant revenue is used than in the cases in which a distance dependent revenue per unit is used. For the AUH and PDA algorithms it is the other way around. The only exception is the performance of the AUH algorithm in the case in which routes are generated at random and only used routes are included in the costs. Then, a case with constant revenue performs better than a case with distance dependent revenue.

Thus, no general conclusion can be made about the performance of heuristics compared to the CAM model. This can be explained in the following way. None of the heuristics take the revenue per unit into account when allocating the demand. On the other hand, the optimal

Table 5.18: Mean difference in average profit of the scenario with variable revenue per unit

No hubs, all routes	KWM	PDA	AUH
Constant revenue	-0.488	-1.645	-0.277
Distance dependent revenue	-0.539	-1.445	-0.246

No hubs, only used routes	KWM	PDA	AUH
Constant revenue	-0.552	-0.786	-0.300
Distance dependent revenue	-0.604	-0.665	-0.313

Hubs, all routes	KWM	PDA	AUH
Constant revenue	-0.549	-1.677	-0.314
Distance dependent revenue	-0.574	-1.448	-0.259

Hubs, only used routes	KWM	PDA	AUH
Constant revenue	-0.615	-0.841	-0.377
Distance dependent revenue	-0.634	-0.673	-0.321

model does take the revenue into account during the allocation. The optimal model is thus, contrary to the heuristics, able to allocate the most profitable demand. The heuristics will probably give better results for one of the revenue definitions, but it cannot be predicted for which one. Which revenue definition will lead to better results can differ between heuristics, as can be seen in the table.

5.3.4.4 Scenario 3: Variable number of routes

This section explains the influence of the number of routes on the performance of the different heuristics compared to the optimal model. Therefore, the average profit of all methods are given in table 5.19. The table is again divided in four subtables, each showing the average profits of a specific case concerning the inclusion of hubs and the way costs are calculated. Up to now, the AUH algorithm performed always best of the heuristics. Table 5.19 shows another order of the performance of the heuristics in some cases. It can be seen that the KWM algorithm outperforms the other heuristics when only three routes are considered. Furthermore, the KWM algorithm performs also best of the heuristics when five routes are considered and hubs are included in the routes. In these cases, the AUH algorithm is the second best heuristic. The PDA heuristic has the least performance. In all other cases, the AUH algorithm outperforms the other two heuristics.

Thus, for cases with only a few routes, the order of the performance of the heuristics is changed with respect to the cases seen earlier. The AUH algorithm performs worse than the KWM algorithm in those cases. The explanation for this can be found in the way the demand is allocated in the two algorithms. Both algorithms start with allocating the demand in the upper-left corner of the demand matrix and iterate thereafter through the demand matrix. When only three or five routes are considered, it is not possible to allocate all demand, so the lowest rows of the demand matrix are highly unlikely to be reached by the algorithm. The difference in the allocation method of the two heuristics is that the KWM algorithm allocates

Table 5.19: Average profit in billion $ for the scenario with variable number of routes

No hubs, all routes	KWM	PDA	AUH	CAM
3 routes	0.791	0.123	0.409	1.485
5 routes	0.764	-0.061	0.939	1.699
7 routes	0.541	-0.522	0.885	1.173
10 routes	-0.130	-1.329	0.195	0.269

No hubs, only used routes	KWM	PDA	AUH	CAM
3 routes	0.791	0.310	0.423	1.485
5 routes	0.766	0.434	0.948	1.700
7 routes	0.541	0.458	0.941	1.369
10 routes	-0.130	0.455	0.536	1.238

Hubs, all routes	KWM	PDA	AUH	CAM
3 routes	0.754	0.259	0.453	1.448
5 routes	0.812	-0.124	0.768	1.725
7 routes	0.489	-0.514	0.850	1.147
10 routes	-0.249	-1.450	0.053	0.156

Hubs, only used routes	KWM	PDA	AUH	CAM
3 routes	0.754	0.416	0.478	1.448
5 routes	0.812	0.443	0.792	1.725
7 routes	0.490	0.438	0.909	1.340
10 routes	-0.249	0.399	0.502	1.191

only direct demand, which means that only demand pairs with origin and destination on the same route are considered. The AUH algorithm on the other hand, can also allocate demand by using a transhipment between two ships. Demand that is satisfied using a transhipment movement uses capacity on at least two routes. Furthermore, the path between the origin and destination ports is usually longer, because the demand has first to be transported to a hub and thereafter from the hub to the destination port in stead to directly from the origin to the destination port. Thus, it is likely that the AUH algorithm uses a lot of capacity by allocating some demand through a hub. This capacity is then unavailable for the demand pairs that are considered later. Therefore, less demand can be allocated, which results in less revenue and thus less profit. When hubs are included in the routes, more demand can be allocated using a hub, so this problem will occur in a larger content than when routes are generated at random. Therefore, the AUH algorithm performs sometimes less when hubs are included in the routes than when routes are generated at random.

Table 5.20 denotes the mean of the relative difference in the average profit of the heuristics with respect to the optimal model. The table shows for the PDA algorithm a difference between cases in which all costs are considered and cases in which only costs of used routes are considered. When all routes are considered, the PDA algorithm performs better with less routes, while it performs better with more routes when only used routes are included in the costs. The KWM algorithm performs in all cases better when less routes are included and the performance of the AUH heuristic increases with the number of routes until seven routes are included. When ten routes are included, the performance decreases again.

When the number of routes included in the model increases, the AUH algorithm is able to satisfy relatively more demand compared to the optimal model, because the available capacity is much higher than the needed capacity. This results in higher revenues and thus higher costs. When all costs are considered, the costs of all methods are about the same. Thus, when a larger part of the demand is satisfied by the heuristics with respect to the CAM model, the relative difference in average profit compared to the optimal model will become closer to 0 for the KWM and AUH algorithms.

Table 5.20: Mean relative difference in average profit of the scenario with variable number of routes

No hubs, all routes	KWM	PDA	AUH
3 routes	-0.467	-0.917	-0.724
5 routes	-0.550	-1.036	-0.447
7 routes	-0.539	-1.445	-0.246
10 routes	-1.485	-5.942	-0.274

No hubs, only used routes	KWM	PDA	AUH
3 routes	-0.467	-0.791	-0.715
5 routes	-0.549	-0.745	-0.442
7 routes	-0.604	-0.665	-0.313
10 routes	-1.105	-0.633	-0.567

Hubs, all routes	KWM	PDA	AUH
3 routes	-0.479	-0.821	-0.687
5 routes	-0.529	-1.072	-0.555
7 routes	-0.574	-1.448	-0.259
10 routes	-2.600	-10.314	-0.658

Hubs, only used routes	KWM	PDA	AUH
3 routes	-0.479	-0.712	-0.670
5 routes	-0.529	-0.743	-0.541
7 routes	-0.634	-0.673	-0.321
10 routes	-1.209	-0.665	-0.578

The effect of the number of routes on the performance of the heuristics depends on other characteristics of the case. When all routes are considered, the performance of the AUH heuristics increase with more routes. This is because the available capacity increases when the number of routes increases. When the available capacity increases, the unused capacity of the optimal model also increases. This means that the heuristics have more space to allocate some demand non-optimal. So, the relative part of demand allocated by the heuristics compared to the optimal model increases, which results in higher revenues compared to the optimal model and thus to higher profits. However, when the number of routes increases, the costs become too high to obtain (high) profits. Furthermore, the profit of the CAM model also decreases, so the small absolute differences, can become high relative differences in this case.

This explains the decrease in performance of the AUH algorithm with respect to the CAM model when ten routes are considered.

In cases where only costs of used routes are incurred, the PDA and AUH algorithm perform better when more routes are included. The PDA algorithm always use only a few routes, but can choose between more routes in these cases. Apparently, the algorithm can then choose better routes to use. The reason that the AUH algorithm performs better with more routes is probably about the same as just explained. Apparently, the algorithm does not use too many routes and chooses profitable routes to use.

The performance of the KWM algorithm decreases with the number of routes in all cases. Apparently, the relative larger part of allocated demand when more routes are used, which leads to relative higher revenues uses too many or cost inefficient routes which lead to relatively higher costs.

In scenarios with different number of included routes, the computational time of the methods also becomes important, because the problem size increases. Therefore, in table 5.21 the average computational times of the four methods are given when the model is solved with different number of routes. Again, no distinction is made between cases with or without hubs and cases in which costs of all routes or only used routes are included, because the average computational times in these different cases hardly differ. The changes in average computational times for different number of routes are comparable with that of diiiferent number of ports. The computational time of the AUH heuristic again hardly increases when the number of ports increases. Furthermore, the computational times of the other two heuristics and the optimal CAM model increases with the number of ports, where the increase is highest for the optimal CAM model. However, the average time needed to solve an instance with 10 routes is still reasonable for the CAM model.

Table 5.21: Average computational times for the scenario with variable number of routes

	KWM	PDA	AUH	CAM
3 routes	0.040	0.087	0.077	0.170
5 routes	0.063	0.119	0.078	0.395
7 routes	0.088	0.158	0.077	0.726
10 routes	0.121	0.193	0.078	1.341

5.3.4.5 Scenario 4: Variable transhipment costs

In the last scenario, the influence of different transhipment costs on the performance of the heuristics are described. The order in which the methods perform can be found using table 5.22. This table shows again the average profit for the different methods in the different cases. For all cases, the optimal model has the highest profit, followed by respectively the AUH algorithm, the KWM algorithm and the PDA algorithm.

Table 5.23 shows the mean of the relative difference in average profit between the heuristics and the optimal model. It can be seen that the average performance is in all cases about the same for the different transhipment costs. Thus, the performance of the heuristics compared to the CAM model does not depend on the used transhipment cost.

Table 5.22: Average profit in billion $ for the scenario with variable transhipment costs

No hubs, all routes	KWM	PDA	AUH	CAM
$0	0.568	-0.477	0.853	1.239
$200	0.541	-0.522	0.885	1.173
$400	0.538	-0.451	0.933	1.207

No hubs, only used routes	KWM	PDA	AUH	CAM
$0	0.570	0.449	0.881	1.305
$200	0.541	0.458	0.941	1.369
$400	0.538	0.442	1.010	1.361

Hubs, all routes	KWM	PDA	AUH	CAM
$0	0.522	-0.482	0.847	1.187
$200	0.489	-0.514	0.850	1.147
$400	0.521	-0.545	0.746	1.168

Hubs, only used routes	KWM	PDA	AUH	CAM
$0	0.523	0.454	0.876	1.247
$200	0.490	0.438	0.909	1.340
$400	0.530	0.404	0.782	1.359

Table 5.23: Mean relative difference in average profit of the scenario with variable transhipment costs

No hubs, all routes	KWM	PDA	AUH
$0	-0.542	-1.385	-0.312
$200	-0.539	-1.445	-0.246
$400	-0.554	-1.373	-0.227

No hubs, only used routes	KWM	PDA	AUH
$0	-0.563	-0.656	-0.325
$200	-0.604	-0.665	-0.313
$400	-0.605	-0.675	-0.258

Hubs, all routes	KWM	PDA	AUH
$0	-0.560	-1.406	-0.286
$200	-0.574	-1.448	-0.259
$400	-0.554	-1.467	-0.361

Hubs, only used routes	KWM	PDA	AUH
$0	-0.581	-0.636	-0.297
$200	-0.634	-0.673	-0.321
$400	-0.610	-0.703	-0.425

The performance of the PDA algorithm only depends on the considered case. When only used routes are considered, the performance is better than when all routes are considered. In general, changing the transhipment cost does not influence the performance of the heuristics.

5.4 Extension: include route cost in the CAM model

In the cargo allocation model, it is assumed that the capital, operating, port and fuel costs are fixed for a route network. Therefore, these costs are not included in the objective function. However, it is not guaranteed that the most cost-effective routes are chosen when not all routes of a given route set are needed to satisfy the demand. The overall model can possibly be improved when the most cost-effective routes of a route set are given and routes that are not used are deleted from the set. Then, the costs of routes have to be included in the objective function of the cargo allocation model.

The capital, operating, port and fuel costs of each route in a route set are known on forehand. Furthermore, it can be determined on forehand how many weeks are needed to sail each ship route. However, it is not yet known whether a route is used or not. Therefore, an additional variable has to be introduced that says whether cargo is assigned to a route or not. This variable can easily be made for each route. However, the model will become integer in this way, which increases the solving time.

Another possibility is to introduce a continuous variable that ranges between 0 and 1. In this variable, the maximum utilization of a ship is saved. Now, the cost of the routes are multiplied by the maximum utilization in stead of a 0/1 variable. The advantage of this method is that the model is still linear. The route costs are included as much as possible.

Introduce the following new parameters:

$CapC_{s_1}$	Yearly capital cost of a ship sailing on ship routes_1
OpC_{s_1}	Yearly operating cost of a ship sailing on ship routes_1
$PortC_{h_1}$	Cost of visiting port h_1
$NrVis_{h_1,s_1}$	Number of visits of port h_1 on ship route s_1
$FuelC_{s_1}$	Fuel cost in \$/nm of a ship sailing on ship route s_1
$Dist_{h_1,h_2}$	Distance in nautical mile between port h_1 and port h_2
RTT_{s_1}	Time in weeks needed to complete one round tour of ship route s_1

Furthermore, let $MaxU_{s_1}$ be the maximum utilization at route s_1, When route costs are included in the cargo allocation model, the objective function 5.1 changes to

$$
\begin{aligned}
\max \sum_{h_1,h_2,s_1} & Rev_{h_1,h_2}\left(DF_{h_1,h_2,s_1} + \sum_{t_1} FTT_{h_1,t_1,h_2,s_1}\right) \\
& - \sum_{h_1} Hand_{h_1}\left(\sum_{t_1,h_2,s_1}\left[FTT_{h_1,t_1,h_2,s_1} FTT_{h_2,t_1,h_1,s_1}\right] + \sum_{h_2,s_1}\left[DF_{h_1,h_2,s_1} + DF_{h_2,h_1,s_1}\right]\right) \\
& - \sum_{t_1} Tran_{t_1}\left(\sum_{t_2,h_2,s_1,s_2\neq s_1} FBT_{t_1,t_2,h_2,s_1,s_2} + \sum_{h_2,s_1,s_2\neq s_1} FFT_{t_1,h_2,s_1,s_2}\right) \\
& - 52\sum_{s_1} MaxU_{s_1}\left(\sum_{h_1} PortC_{h_1} NrVis_{h_1,s_1} + \sum_{h_1,h_2\in p(h_1,s_1)} FuelC_{s_1} Dist_{h_1,h_2}\right) \\
& - \sum_{s_1} MaxU_{s_1} RTT_{s_1}\left(CapC_{s_1} + OpC_{s_1}\right)
\end{aligned}
\tag{5.11}
$$

Furthermore, additional constraints are needed to find the value $MaxU_{s_1}$ for each ship route s_1. These constraints have to assign the maximum utilization on ship route s_1 to $MaxU_{s_1}$. The constraints will replace constraints 5.3 and are given by

$$
CF_{h_1,h_2,s_1} \leq MaxU_{s_1} Cap_{h_1,h_2,s_1} \quad \forall h_1, h_2 \in p\left(h_1, s_1\right) \tag{5.12}
$$

In the remainder of this thesis, this model will be referred to as the extended cargo allocation model or the extended CAM model.

For some routes in a route set the value of $MaxU_{s_1}$ will be equal or close to 1, while for other routes the value will be (close to) 0. All routes for which $MaxU_{s_1} = 0$ are deleted from the route set. However, it will probably be profitable to delete also routes for which $MaxU_{s_1}$ is small. Therefore, the next procedure is followed:

1. Initialize the best profit $P = 0$ and the current network N.
2. Set P_{new} equal to the profit obtained when solving the extended CAM model with the initial route set.
3. Repeat the following as long as $P_{new} > P$.
   (a) Set $P = P_{new}$ and $N = N_{new}$.
   (b) Delete all routes for which $MaxU_{s_1} \leq \sum_{s_1} MaxU_{s_1}/NrR$, where NrR is the number of routes in the current route set. Set the new network N_{new} equal to the obtained network after deleting the routes.
   (c) Set P_{new} equal to the profit obtained when solving the extended CAM model with the new route set.

The optimal network and profit are given by P and N when the algorithm terminates. This algorithm will be referred to as the allocation procedure. In the algorithm routes are deleted from the route set when the maximum percentage of capacity used at the route is lower than the average over all routes. The total demand delivered will probably be reduced when routes are removed from the set, because total capacity is reduced. However, the problem remains feasible, because not all demand have to be satisfied.

When solving the extended CAM model in the first iteration, it is also possible to add the following set of constraints to the model: $MaxU_{s_1} \geq \alpha$ for all s_1 and a certain value of α. In this case, routes will only be used when they are used for a certain fraction of the total capacity. However, when a very profitable part of the demand is served on a route with large capacity, the maximum percentage of capacity used on this route can be below α, while the profit of the served demand would cover the costs of these route. Then, in the first iteration a profitable route will already be deleted when these constraints are added. With the algorithm described above, this route will only be deleted when the profit increases when the route is removed from the route set.

5.4.1 Comparison with CAM model

The results of the extended CAM model can be compared with the results of the CAM model. However, Route sets are randomly generated (as will be explained later in chapter 7) with three different number of clusters. The clustering process will be explained in the next chapter.

In this thesis, a genetic algorithm based method will be used to change the routes in order to find the optimal route network. In each iteration of the genetic algorithm, a set with a specified number of route networks is generated by selecting and changing networks that were previously obtained. In chapter 8, this method is described and the way in which the networks are selected is explained. Thus, not the exact profit of a route network, but the probability of selecting networks is important when running the overall model. A method that gives lower profits, but in which the selection probability of the networks is very similar to the selection probability of the networks when the optimal profits are used, can also be used to run the model.

Therefore, the three methods are compared in the following way. For each network, the profit of the network using each of the three methods is determined. Thereafter, the optimal profit of the route network is defined as the maximum profit obtained with the three methods. Then, for each route, the selection probability is calculated for each of the three methods and the optimal profits. The selection probability is calculated using the method described in chapter 8. Finally, the sum of the squared deviations in the selection probability between each of the three methods and the optimal profits is determined and used in the comparison together with the average computational time.

The route networks are generated using the method described in chapter 7 with the probability of including a port in a route varying between 0.2 and 0.6. Furthermore, three different number of clusters are used: 10, 12 and 15. In total, 100 networks per number of clusters are generated.

Table 5.24: Performance of the extended CAM model compared to the CAM model

		CAM model	Extended CAM model	Allocation procedure	Random
10 clusters	SSD	0.111	0.0222	0	0.059
	ART (s)	2.968	4.356	5.846	-
12 clusters	SSD	0.129	0.024	0	0.044
	ART (s)	8.827	15.394	19.404	-
15 clusters	SSD	0.123	0.047	0	0.039
	ART (s)	18.290	32.534	41.734	-
Total	SSD (10^{-3})	0.805	0.230	0	0.425
	ART (s)	11.981	21.108	26.848	-

In the allocation procedure explained in the previous section, the extended CAM model is solved as long as the profit increases. However, it is also possible to solve the extended CAM model only once. In this section, three methods are compared to each other: the CAM model, the extended CAM model (solved only once) and the allocation procedure that repeatedly calls the extended CAM model. In table 5.24, the sum of squared deviations (SSD) between the selection probability of networks obtained with these three methods and the selection probability of the networks when the optimal profit is used, and the average running times (ART) of the methods are given for three different number of clusters. The overall sum of squared deviations are not obtained by summing the deviations for the different number of clusters. They are obtained by calculating the selection probability of each individual network and comparing it with the selection probability of the networks obtained by using the optimal profit when all route networks in the three different categories are combined. Furthermore, in the last column the sum of squared deviations between random selection and the selection probabilities obtained by using the optimal profit of the networks, is given.

From table 5.24, it can be seen that the allocation procedure will always lead to the highest profit (the sum of squared deviation for this method is always 0). This could have been expected, because the extended CAM model is called as long as the profit increases. Therefore, the profit of the other methods can at most be the same as the profit obtained by this procedure. When the deviation in selection probabilities are compared, it can be noted that the CAM model performs always worse than a random selection method. Therefore, it is not plausible to use the CAM model in the overall model.

When the extended CAM model and the allocation procedure are compared to each other, it can be seen that the extended CAM model performs in general only a bit better than a random selection method. Furthermore, the difference in computational times is relatively small. Therefore, it is chosen to use the allocation procedure in the overall model used in this thesis.

5.5 Evaluation

In this chapter, a linear programming model to solve the cargo-routing problem is introduced. This model solves the cargo-routing problem to optimality. Therefore, research question 1 can be answered positively for the cargo-routing problem.

In section 5.3, research question 3 is considered. Three existing heuristics (KWM, AUH and PDA algorithms) are presented and their performances are compared to that of the cargo allocation model. Different scenarios are considered to investigate whether the CAM model and the heuristics perform invariably or not. First, the performance of the different heuristics are compared to each other. In almost all scenarios, the AUH algorithm has the best performance of the heuristics. However, the AUH algorithm performs on average at least 20% worse than the optimal CAM model.

The computational time of the AUH heuristics is on average about 5-10 times smaller than that of the cargo allocation model. However, the CAM model can be solved in less than a second in most scenarios. Therefore, the increase in profit is more important than the increase in computational time. Thus, in the remaining of this thesis, the cargo allocation model (or its extension) will be used to solve the cargo-routing problem.

Finally, in section 5.4 an extension of the cargo allocation model in which route costs are considered in the objective function is discussed. In this extension, the CAM model is adjusted to a model in which the route costs are included in the objective function. Furthermore, a procedure is made in which the extended CAM model is solved repeatedly. After each solve, the routes that are (almost) not used are deleted from the route network. The procedure stops when the profit of the network decreases.

The performance of the extended CAM model and the allocation procedure are compared to the performance of the CAM model. Although the running time of the allocation procedure is increased compared to that of the (extended) CAM model, the performance based on the profit is much better. Therefore, the allocation procedure will be used in the overall model explained in this thesis.

Chapter 6

Aggregation of ports

The (extended) cargo allocation model can be used to find the optimal cargo allocation when the set of routes is given. However, when large instances of the cargo allocation model have to be solved repeatedly, the method becomes very time consuming. One way of reducing the computational time is to reduce the size of the problem. Thus, in this chapter research questions 5, 5a and 5b are considered. These questions are:

5. Can the size of the problem instances be reduced in order to increase the speed of the solution method?

    (a) If the problem size can be reduced, can the smaller problems be solved using only mathematical programming techniques?

    (b) Which methods can be used to convert the solution to the initial problem size?

The size of a problem instance depends on the number of variables and constraints included in the model. Thus, to reduce the problem size, a reduction in the number of variables and constraints is needed. The number of variables and constraints depends on the number of ports included in the problem. Therefore, the problem size can be reduced by reducing the number of included ports. This can be done using an aggregation method to cluster ports. The port clusters will become the new input in the model. After solving the LP problem, the port clusters should be disaggregated into the original ports to obtain a solution for the original problem.

6.1 Preprocessing

In this chapter, methods to aggregate and disaggregate ports are described. The aggregation of ports reduces the size of the (extended) cargo allocation model and thus the computational time needed to solve the model. This section describes the steps that have to be performed before the aggregation method can be executed. For each cluster of aggregated ports one port (the central port) is chosen as the port that will be visited by ships in the model. Feeder services will be used to serve the demand between the central port and the other ports in the cluster.

Effect of the number of ports on the computational time
The desired number of clusters depends on the computational time of the model compared to the size of the problem instance. However, decreasing the number of clusters leads to an increase in the cargo on the feeder services. Therefore, probably more ports are reallocated to the direct liner services, but this is done in a heuristical way. It will then probably be harder to find a good approximation of the optimal solution. So, a tradeoff has to be made between the computational time of the model and the quality of the solution. In table 6.1 an overview is given on the computational time of the CAM model for different number of clusters. The CAM model is solved for twenty different route networks for each number of clusters. From the table it can be seen that the computational time is increasing exponentially with the number of clusters. The last row of the table, with 58 different ports, denotes the situation in which all ports are included in the model. For this model, ten to fifteen clusters will be reasonable to work with. The number of ports that is given as input for the aggregation method is not restricted. By changing the parameters (as will be explained below), each desired number of clusters can be reached. In this thesis, different number of clusters will be used and the results will be compared.

Table 6.1: Computational time in seconds for different number of clusters

Number of	Computational time		
clusters	Minimum	Average	Maximum
10	0.000	2.968	10.321
12	0.050	8.827	24.476
15	0.092	18.290	72.389
17	0.207	41.749	312.578
20	0.431	102.757	538.663
58	151.340	27038.216	>108,000

As will be explained in the next section, the central port will be the port in the cluster with the largest demand, because feeder services are assumed to be more profitable compared to liner services when less flow has to be shipped. Therefore, it is not reasonable to allow two ports with high demand to be in the same cluster. In this section, it is investigated whether a list can be made containing all ports for which a direct liner service will be preferred over a feeder service. All ports on this list then have to be central ports of a certain cluster. Furthermore, for some ports that have very little demand, a liner service cannot be more profitable than a feeder service. Therefore, also a list containing all ports that are not allowed to be central ports is made. Finally, a third list is made containing all remaining ports (all ports that are included in the model, but not allocated to one of the first two lists). These lists will be used as input in the aggregation method.

Construct lists according to costs and benefits
The construction of the lists can be performed in two ways. First, the costs and benefits of the feeder services compared to the liner service can be calculated and used to determine which service is preferred. For each port the expected feeder costs are calculated and compared to the expected cost of and additional stop by a liner ship to determine whether the port should be a central port in a cluster or not. If the expected feeder costs are higher than the expected liner costs, it is more profitable to make an additional stop in the liner service network than using a feeder service. Therefore, ports with higher expected feeder costs are added to the

list with central ports and ports with lower expected feeder costs are added to the list of noncentral ports.

The expected costs of a feeder service between a port and the central port of the cluster consist of capital and operating costs of the container ship used, the fuel costs of the feeder and the costs of transhipping the loads from liner ships to feeder ships. The expected liner costs consist of the additional capital, operating, fuel and port costs. However, some problems occur when these costs are calculated. The costs of the feeder service can be reasonably good estimated, because the distance between the port and the central port of the cluster and the demand of the ports are known. Although, it is not exactly clear which amount of the demand is fulfilled, this can be estimated reasonably well, so good estimates of the feeder capacity and transhipping costs can be made.

The costs of the liner service, on the other hand, are much more uncertain. In this case, port costs are the only costs that are known on forehand. The additional capital and operating costs are dependent on the length of the original route and the additional distance that has to be covered. The increase in fuel costs is also dependent on the additional distance. The aggregation of ports is done before the routes are known, so both the route time and the additional distances are unknown. In this thesis it is assumed that each port on a route is served once a week. Thus, the number of ships needed on a route equals the route time in weeks. Adding an additional port on an existing route can increase the number of ships needed, which will result in a significant increase in costs.

In most cases, adding an additional port will not be profitable when this causes an increase in the number of ships needed to serve the route. Another possibility is to increase the sailing speed of the ships on the route. In this case, the route time in weeks may remain unchanged, but the fuel costs will increase significantly. However, on forehand the routes are not yet known, so the consequences of adding an additional port are unknown. Therefore, as long as the routes and ship allocation are unknown, it cannot be stated whether adding a port will be profitable or not. Thus, this method cannot be used to construct the three lists of ports.

Construct lists according to total demand

The other way of constructing the lists is to compare the total demand or throughput of the different ports. When a port has more throughput, the liner service is expected to be more efficient. The throughput of a port is not known on forehand, but it is assumed that the throughput is higher for ports with higher total demand. The demand matrix is an input of the model, so total demand can be determined on forehand and used to estimate the throughput of the port. Ports with very little throughput have to be served by a feeder service, because a liner service will almost certainly lead to higher costs. Next, a way to construct a list of central ports using the expected throughput of the ports is described.

To construct all three lists, first the average total demand of a port is calculated and compared to the total demand of all individual ports. When the total demand of a port is higher than the maximum demand factor, the port is added to the list containing central ports. When the total demand of a port is lower than the minimum demand factor, the port is added to the list containing the noncentral ports. Finally, ports for which the total demand is between the minimum and maximum demand are added to the third list. The maximum and minimum demand factors can be varied to obtain the desired number of port clusters.

Parameter settings
The minimum and maximum demand factors can thus be varied to obtain the desired number of clusters. However, it is chosen to retain the minimum demand factor constant at a value of 0.2 in this thesis, because it does not really influence the number of clusters. The minimum demand factor will only be relevant when a small port lies relatively far from all ports in its neighborhood. Then, the port will be forced to be part of the nearest cluster, although the distance to that cluster is larger than the maximum distance. Thus, only the maximum demand factor will be changed in this thesis. To obtain the desired number of cluster (between the 10 and 15), the maximum demand factor is varied between 1.5 (15 clusters), 1.75 (12 clusters) and 2 (10 clusters). In the results, it will be given how many clusters are included in the model.

The maximum distance will be chosen in such a way that a ship is able to sail from the port to the cluster center and back within a period of one week. However, both the buffer time and both port times have to be considered when determining the round time. Thus, the ship can sail at most 114 hours in a week. With the speed of 22 nm per hour, this gives a maximum distance of 2508 nm. Therefore, the maximum distance between two ports can be 1250 nm.

6.2 Aggregation method

The aggregation method used in this thesis will be described in this section. When the problem instance becomes larger, the computational time of the cargo allocation model increases exponentially. So, for large problem instances, it is very time consuming to solve the cargo allocation model repeatedly. The size of the problem instance decreases when the number of ports is reduced. Therefore, the computational time of the cargo allocation model can be decreased by reducing the number of ports. It depends on the computational time of the (extended) CAM model to which number of ports the problem has to be reduced. However, by changing the input parameters of the aggregation method, the desired number of ports can always be obtained. In this thesis, problem instances up to fifteen ports are assumed to be reasonable.

In a model with aggregated ports, ships stop only once per cluster. For each port cluster, the stop should always be at the same place. Therefore, three major decisions have to be made during the aggregation process. First, the ports that are aggregated into a port cluster have to be determined. Next, one of the ports in a cluster has to be chosen as the central port. Finally, the data of individual ports have to be aggregated to port cluster data.

Determine distance between ports in a cluster
First, the method used to determine the ports that are aggregated into the same cluster is considered. In this thesis, it is assumed that ports are aggregated based on distance. Ports that are relative near to each other are clustered. An upper bound on the distance between two ports that belong to the same cluster can be imposed. However, a problem can occur when this upper bound has to hold for each combinations of two ports in a cluster. This can best be explained using a small example.

Suppose for example, that the upper bound on the distance is 5. Now consider a situation of three ports named A, B and C where the distance between ports A and B is 3, the distance between ports B and C is 4 and the distance between ports A and C is 6. Now, ports A and B belong to the same cluster as the distance between these ports is smaller than 5. The same holds for ports B and C. Combining these results, ports A, B and C all belong to the same cluster. However, the distance between ports A and C is 6, which indicates that ports A and C do not belong to the same cluster. So, the exact composition of the cluster is unclear.

This problem can be solved by comparing the distance between a random port and a predetermined port with the upper bound. It seems reasonable to compare the distance between a random port and the port in the cluster that is visited on the route, because the cargo has to be transported from the central port to the other ports in the cluster. So, first the port that is visited in a cluster (the central port) has to be determined. In the preprocessing, a list is made containing ports that should be central ports. Furthermore, a list of ports that are not allowed to be central ports (noncentral ports) is made in the preprocessing. Finally, a list with all remaining (intermediary) ports is made. These lists can now be used to design the clusters as will be explained in the remaining of this section.

Determine cluster design

Using the three lists constructed in the preprocessing, the following steps can be performed.

1. For each port that is not on the list of central ports, save the nearest central port and the distance to the this central port.
2. For each central port, add the ports for which the saved nearest port equals the central port to the cluster containing this central port if the saved distance is less than or equal to the maximum distance between ports in a cluster.
3. Sort the intermediary ports that are not yet allocated to a cluster according to nonincreasing total demand.
   (a) As long as not all intermediary ports are allocated, add the unallocated intermediary port with the highest total demand to the list of central ports (and remove it from the list of intermediary ports).
   (b) Determine for each port (allocated and unallocated) whether it is nearer to the new central port than to the saved nearest central port. If this is the case, change the saved central port and the distance to the nearest central port. Furthermore, remove the port from the cluster it currently belongs to (if it is allocated) and add it to the cluster that contains the new central port if the distance between the port and the central port is less than or equal to the maximum distance between ports in a cluster.
4. Check whether all noncentral ports are allocated to a cluster. If a noncentral port is not yet allocated, add it to the cluster that contains the central port to which the noncentral port is closest to independent of the distance between those ports.

The main idea of the algorithm is that first clusters are made for each central port. Thereafter, each intermediary and noncentral port is allocated to the nearest cluster, if the distance to the cluster center is at most equal to the maximum distance. Then, it is checked whether all intermediary ports are added to a cluster. When some intermediary ports are still unallocated, the largest is selected and a cluster is initialized with the intermediary port as central port. Next, all ports for which it is the closest central port are (re)allocated to this cluster. Thus, when (some of) these ports are already allocated, they are moved from their previously allocated cluster to the new cluster. This is repeated until all intermediary ports are allocated. Finally, it is checked whether all noncentral ports are allocated to a cluster. If unallocated noncentral ports exixt, these ports are allcoated to the nearest cluster. Note that for these ports the maximum distance between ports in the same cluster is exceeded. However, it is assumed to be more profitable to add these ports to a cluster and serve their demand using feeder services than to serve these ports with the liner ships.

Data aggregation
Now, the data aggregation process will be considered. Relevant port data in the model are distance, demand, port cost, transhipment cost, (un)loading cost and port time. The distance, costs and port time only depend on the port at which the ship stops. Therefore, for these data the port cluster data is the same as the individual port data of the central port. The demand data depends also on the demand at the other ports in the cluster. Cluster demand equals the sum of the individual port demand. Note that demand between ports in the same cluster disappears during the aggregation process. This demand can be reviewed after the disaggregation process.

6.2.1 Cluster design

As mentioned earlier, in this thesis scenarios with ten, twelve and fifteen clusters are considered. In this section, the design of these clusters is provided.

In tables C.1-C.3 in appendix C the design of the clusters in the three different scenarios are given. Furthermore, figures C.1-C.3 in the same appendix show the geographical representation of the clusters in these scenarios. In the tables, the central ports of the clusters are given on the first row. The other rows show all ports (including the central port) that are part of the cluster. The clusters are given in geographical order starting in Asia. In the figure, a cluster is represented with a light blue plane and the ports are presented with a blue marker. The central port can be recognized by the black dot in the marker.

From the figures, it can be seen that the clusters are indeed constructed based on their geographical location. In some cases, two clusters are located near each other. In these cases, both clusters contain a large port that has to be a central port.

When a scenario with twelve clusters is considered in stead of ten, it can be seen that two clusters, namely that with central ports Shanghai and Hong Kong are split in two new clusters. When the number of clusters is increased to fifteen (instead of twelve), the cluster with central port Shanghai is now splitted into three new clusters. Furthermore, the cluster with central port Hamburg is splitted in two new clusters. Thus, the cluster with central port Shanghai in the scenario with ten clusters contains a lot of relatively large ports. This cluster contains also many ports compared to the other clusters, so it is quite logical that this cluster is splitted in scenarios with more clusters. When the number of clusters is increased, these ports become central ports of new clusters.

6.3 Disaggregation method

The cargo allocation model can be executed with the clusters as determined in the previous section as input. The output of the model becomes the cargo flow between the clusters. In practice, it is necessarily to know the exact route of each load from origin port to destination port. Therefore, the cargo flows from and to clusters have to be disaggregated in cargo flows from and to individual ports in the clusters. In first instance, for each port in the cluster (except the central port) a feeder service is added from the central port to this port. Later on, feeder services containing more ports and the profitability of an extra stop at the main route in stead of a feeder service are considered. The disaggregation process consists of the determination of the origin and destination port for each unit of cargo flow that is obtained from the model.

The method explained in Fagerholt (2004) can be used to determine the routes and cargo allocation in the feeder network. However, when too many ports are clustered in one cluster, this method can become very time consuming. A method that starts with many routes in a feeder networks and tries to combine routes would be a lot faster. Thus, in this thesis another method to disaggregate the flows is chosen. This process will be explained below.

Disaggregate cluster flow to port flow
Consider two port clusters I and J that are output of the cargo allocation model. Determine the total cargo transhipped between these clusters in the model. This amount of cargo has to be divided over the possible combinations of real ports that belong to the port clusters. Thereto, determine first all ports i belonging to cluster I and all ports j belonging to cluster J. Note that clusters can also consists of only one port. Then i simply equals I and the same holds for port cluster J. Now, order all possible combinations (i, j) according to non-increasing revenue per unit.

Thereafter, allocate as much cargo as possible to the first port combination and repeat this with the following port combination until the total cargo transhipped is allocated to the port combinations. Thus, the combination with the highest revenue per unit will be considered first. The maximum amount of cargo that can be allocated to a combination equals the minimum of the demand between the considered combination and the unallocated transhipped cargo. Note, that the unallocated transhipped cargo has to be updated each time a port combination is considered. Because the cluster demand equals the sum of the individual port demand of the ports in the cluster and all possible combinations are considered in the disaggregation method, the total transhipped cargo is always fully allocated using this method. Finally, this procedure is repeated for all combinations of two (aggregated) ports of the cargo allocation model.

Construct initial feeder services
When all combinations are viewed and the cargo allocation between each two real ports are known, the size of the feeder services can be determined. In first instance, for each noncentral port in a cluster, a feeder service is made. This feeder ship will then sail from the central port of the cluster to the noncentral and back to the central port. The size of the ship can be found when considering the cargo transhipped from and to the noncentral port. These amounts will not be on the ship at the same time, so the maximum of the amount of cargo transhipped to and the amount transhipped from the noncentral port is the maximum load

on the feeder ship.

The needed size of the feeder ship is then the minimal size that can transport the maximum load. Note that only feeder services that sail with a frequency of once a week are considered. Exemptions are only made for ports that are placed in a cluster because their demand is too low, but cannot be served within one week with a direct feeder route from the central port of the cluster. However, it is also possible to consider feeder services that sail more times per week. The size of one ship needed will then becomes smaller. However, the costs will become higher, most of times. When for example a capacity of 2000 TEU per week is needed, one can choose between a feeder service with size 2000 TEU and frequency once a week and a feeder service with size 1000 TEU that sails the route twice a week. The cheapest of the two options will then be preferred, but in this thesis this is not considered.

6.4 Improvement steps

In the previous section, the flow between clusters, obtained from the cargo allocation model, is disaggregated to flow between individual ports. However, during the disaggregation process, only the revenue per unit is included in the decision process. Because feeder services are used to transport the demand from the central port in the cluster to the other ports, it is possible that the profit can be increased by reallocating some of the flow in such a way that some feeder services can be reduced in size. Another possibility is to exchange a port between two existing feeder services. When this port is removed from a feeder service that only visits this port and the central port in the cluster, this old feeder service is removed. So, this method will lead to a reduction in the number of feeder services. Exchanging a port can for example be profitable when the ports visited by the feeder services are near each other. These two steps (reducing the size of the feeder service and exchanging ports between feeder services) will be considered at the same time. Furthermore, it can be profitable to visit certain ports in the main route in stead of using a feeder service. Finally, not all demand is profitable when transhipped using a feeder service. Because this demand is profitable when it is only transhipped over a liner service, it is included in the cargo allocation model. Now, this demand is removed when it has to be served by a feeder ship. In this section these improvement steps are discussed.

6.4.1 Reducing the feeder service network

In the disaggregation algorithm the feeder sizes are not used to allocate the flow between individual ports in a cluster. Therefore, it is very unlikely that the capacity of feeders is fully used. Probably, some feeder services exist for which the capacity can be reduced when the allocated flow is reduced a bit. Furthermore, in first instance, a feeder service from the central port to this port and back to the central port is used for each noncentral port in the cluster. Because ports in a cluster are all relatively near to each other, it can be profitable to serve more ports on one feeder service. This section describes a method that can be used to reduce the sizes and number of the feeder services as much as possible without causing a reduction in profit.

The reduction in the feeder service network can thus be accomplished in two ways. It is not known on forehand which way will lead to the highest increase in profit. Therefore, a method containing three steps is used in this thesis. In the first step, the highest increase in profit when only reducing the size of one of the feeder services is determined. Both the increase in profit and the feeder service to decrease is saved. The second step determines the highest increase in profit when a port is exchanged between two existing feeder services. Now, the increase in profit, the old feeder services and the new feeder services are saved. In the third step the increase in profit of both steps are compared and the most profitable change is made. Next, the three steps are explained in more detail.

6.4.1.1 Reducing the size of a feeder service

In first instance, all feeder services are direct services between the central port in a cluster and a noncentral port in the same cluster. In this case, only two cases have to be distinguished when reducing the size of a feeder service. The noncentral port can be the origin port of a cargo flow, in which case the cargo is on board when the ship sails from the noncentral port to the central port of the cluster or the noncentral port is the destination port of a cargo flow and the cargo is on board when the ship sails from the central port of the cluster to the noncentral port. In both cases, the cargo is only at one of the two legs on board, so only one leg has to be considered for each cargo flow. However, when ports are exchanged between feeder services, some feeder services are created that visit more than one noncentral port. In this case more legs have to be considered when a cargo flow is viewed. This makes the size reducing process more complicated.

Algorithm
The next algorithm describes the steps that have to be performed to determine the increase in profit when the size of a feeder service is reduced. Note that no real changes are made in the algorithm. So, when the algorithm starts over in step 1, the data is still the same as at the beginning. If a change is mentioned in the algorithm it is a temporarily change, which only holds during one iteration of the algorithm.

1. Consider a cluster and a feeder service in the cluster. Determine the capacity of the feeder service when it is reduced by one size.
2. Determine the reduction needed on each leg of the feeder service.
3. Repeat the following as long as the sum of the reduction needed over all legs is larger than 0 and not all port combinations are considered.
    (a) Exchange as much cargo as possible between the port combinations that are not yet considered and have the lowest revenue decrease.
    (b) Update the reduction needed on each leg.
4. Check whether the sum of the reduction needed is 0.
    (a) If the sum is 0, determine the increase in profit, when the exchanges are performed.
        i. If the increase in profit is higher than the highest increase found earlier, save the new increase in profit and the reallocation of demand needed to decrease the feeder size.
    (b) Else, the reduction is not possible.

5. If all feeder services are considered, then stop. Else, return to step 1.

Determine the reduction needed of a leg
The algorithm above gives a brief overview of the steps that have to be taken to determine the most profitable reduction in the size of a feeder service. The algorithm is very useful to create quickly a good insight in the method. However, some steps of the algorithm have to be explained in more detail. In step 2 the reduction needed on each leg of the feeder service has to be determined. To do this, first the flow on each leg of the algorithm has to be determined. Thereto, the legs over with the cargo is transported, have to be determined. For each leg, the flow on the leg equal the sum of all cargo flows that are transported over the leg. The reduction needed can now be found by subtracting the flow over the leg from the new feeder ship capacity. Note that the minimum value that the reduction needed can take on each leg is equal to 0.

Determine port combinations between which cargo can be exchanged
Step 3a of the algorithm requires a list of port combinations $((P_1, P_2), (P_3, P_4))$ between which cargo flows can be exchanged. An element on the list means that a cargo flow from port P_1 to port P_2 is changed into a cargo flow from port P_3 to port P_4. This list has to be made before the algorithm is performed. Valid combinations are combinations in which ports P_1 and P_3 are part of the same cluster and ports P_2 and P_4 belong to the same cluster. One of these clusters have to be the considered cluster. However, two more restrictions are imposed on the combinations, because it will become too complicated when these restrictions are not required.

The first additional restriction is that the port that does not belong to the considered cluster is not allowed to change. This means that either $P_1 = P_3$ or $P_2 = P_4$ (when the considered cargo flow has the origin in the considered cluster, then $P_2 = P_4$ holds, while $P_1 = P_3$ holds when the considered cargo flow ends in the considered cluster). When this restriction is not imposed, the flows on the feeder services in the other cluster have also to be checked on capacity constraints, which would complicate the process more than necessarily.

The other additional restriction is that the new port in the considered cluster is not allowed to be visited on the same feeder service as the old feeder service. This restriction guarantees that the total reduction needed will not increase after a step. Because the goal is to reach a total reduction needed of 0, this is a very useful guarantee.

All combinations of ports P_1, P_2, P_3 and P_4 that satisfy the above restrictions are valid combinations and should be on the list. Note that the list is dependent on the considered cluster, so that for each cluster a different list exists. Next, the revenue decrease of exchanging one unit of cargo has to be calculated for each combination on the list. This can be done by calculating the revenue of satisfying one unit of demand between ports P_1 and P_2 and subtracting the revenue per unit between ports P_3 and P_4 from it. The reason that is spoken of a revenue decrease is because in the disaggregation phase, the flows are allocated to the ports with the highest revenue.

Exchange cargo between port combinations
In step 3a of the algorithm, the port combinations $((P_1, P_2), (P_3, P_4))$ that have the lowest revenue decrease when a unit of cargo is exchanged from port combination (P_1, P_2) to port combination (P_3, P_4) of the list is selected. Then it is investigated how much cargo can be exchanged between these port combinations. The amount equals the minimum of the

unallocated demand between ports P_3 and P_4 and the maximum free capacity of the feeder service between either port P_3 and the central port of the cluster, when port P_3 is in the considered cluster or between the central port of the cluster and port P_4, when port P_4 is in the considered cluster. The amount of cargo exchanged equals now the minimum of the amount that can maximally be allocated and the maximum reduction needed on the legs of the considered feeder service over which the cargo is currently be transported.

Step 3b updates the reduction needed of all legs on the feeder service over which the cargo is currently transported. For these legs, the amount of cargo exchanged is subtracted from the reduction needed. However, when the new reduction needed becomes negative, it is set equal to 0. Steps 3a and 3b are repeated until the reduction needed equals 0 at all legs of the considered feeder service or all combinations of the list are considered.

Check whether the feeder size can be reduced
In step 4 it is checked whether the reduction of the feeder size is possible or not. If the reduction is possible, the increase in profit has to be calculated. This can be done by calculating the difference in capital, operating and fuel costs between the two sizes of feeder services and subtract the decrease in revenue, that is incurred by exchanging cargo flows, from it. When the increase in profit is higher than the highest increase found earlier, the viewed reduction is the most profitable reduction until now and the increase in profit and cargo exchanges needed are saved. Finally, the algorithm is repeated until all feeder services in all clusters are considered.

6.4.1.2 Exchanging a port between two feeder services

In this step a port is exchanged between two feeder services. The cargo allocation does not change during this step, so the revenue and variable feeder costs will also not change. Because the costs on the main route will also stay the same, the only changes will occur in the fixed feeder costs. These costs consist of the feeder capital, operating and fuel cost. Finding a profitable exchange corresponds now to finding an exchange for which the fixed feeder costs are reduced.

Algorithm
Next, the method used to exchange ports will be explained using an algorithm. Thereafter, the steps of the algorithm will again be explained in more details. Note again, that the changes made in the algorithm are only temporarily changes. In this case, each time the algorithm returns to step 4 or step 1, the data is the same as at the beginning. The real changes are only made in the third step of the method (the comparison).

1. Consider a cluster and two feeder services, F_1 and F_2 in the cluster.
2. Determine all noncentral ports that are served by the feeder service F_1.
3. Determine all consecutive port combinations on feeder service F_2.
4. Repeat the following steps as long as not all combinations of a noncentral port and a consecutive port combination are considered.
    (a) Select a combination of a noncentral port N and a consecutive port combination (P_1, P_2).

(b) Remove port combination (P_1, P_2) from feeder service F_2 and add the combinations (P_1, N) and (N, P_2) to F_2. Furthermore, remove port N from feeder service F_1.

(c) Determine the new loads on and capacities of feeder services F_1 and F_2.

(d) Determine the increase in profit obtained by adding port N between ports P_1 and P_2 on feeder service F_2.

i. If the increase in profit is higher than the highest increase found earlier, save F_1, F_2, N, P_1, P_2 and the new highest increase in profit.

5. If all combinations of two feeder services in the same cluster are considered, then stop. Else, return to step 1.

Determine new loads and capacities

Most steps of the algorithm are self-explanatory, however some steps need detailed explanation. In step 4c the new loads and capacities of the feeder services are determined. First, the determination of the new load of feeder service F_1 is considered. When port N was the only noncentral port visited by feeder service F_1, feeder service F_1 will be removed and the new loads and capacity become 0. Otherwise, the cargo allocations from and to port N have to be removed from the loads of all consecutive port combinations, where this cargo was on the feeder ship in the initial situation. Then, the new size of the ship used for feeder service F_1 can be determined by finding the smallest capacity that is equal to or larger than each load between consecutive ports of the service.

For feeder service F_2 a similar procedure can be used. Add the cargo allocation from and to port N to the loads of feeder service F_2. Again, these allocation has to be added to all combination of consecutive ports where the cargo will be on the ship. When the new loads are known, the new size of the feeder ship can be determined in the same way as for F_1.

Calculate increase in profit

In step 4d the increase in profit of the change is calculated. First, compute the feeder capital, operating and fuel costs of both initial feeder services. The sum of all these costs equals the initial fixed feeder costs. Thereafter, the new determined capacities can be used to calculate the new fixed feeder costs of both services. Finally, the increase in profit of this exchange can be calculated by subtracting the sum of the fixed feeder costs of the new feeder services F_1 and F_2 from the initial fixed feeder costs.

Save highest increase in profit

Repeat the above procedure until all possible combinations of a noncentral port of feeder service F_1 and a combination of consecutive ports of feeder service F_2 are considered. Thereafter, select the next cluster until all clusters are considered (step 5). Each time, compare the increase in profit with the highest increase in profit that can be realized by one of the combinations that is considered earlier. When the new profit increase is higher, save the feeder services F_1 and F_2, the noncentral port N and the combinations of consecutive ports (P_1, P_2) and the new highest increase in profit. This is all performed in step 4(d)i of the algorithm. Thus, when all feeder services in all clusters are considered, the most profitable exchange is found and saved.

6.4.1.3 Comparison

After the first two steps, both the most profitable reduction in the size of a feeder service and the most profitable exchange of a port between feeder services are known. Furthermore, the amount of increase in profit is known for both changes. Note, that the increase in profit can also be negative, which corresponds to a decrease in profit (loss), because it is not checked in the first two steps whether the increase in profit is positive or not. First check which increase in profit is the highest, that of the reduction in size or that of the port exchange. Next, check whether this highest increase in profit is bigger than 0. If the increase is higher than 0, make the changes that corresponds to the increase. So, if the highest increase in profit is caused by a reduction in the size of a feeder ship, reduce the saved feeder ship by one size and reallocate the necessarily demand to make this reduction possible. However, if the highest increase is caused by a port exchange, remove the saved port from the first saved feeder service and add this port between the saved combination on the second saved feeder service. Finally, if a profitable change is made, go back to the first step, else the feeder network cannot be improved further using this method, so stop.

6.4.2 Add ports to main route

In this section, it is investigated whether it is profitable to add some ports to the main route and thereby reducing the size of the feeder service network serving those ports. At the moment, only the central port of a cluster is visited on the main routes of the route network. All other ports are served by a feeder service. However, some noncentral ports exist, which have also a large amount of cargo handling movements. Now, the flows are known, it can be calculated whether it is profitable to visit these noncentral ports on one of the main routes. A part of the cargo flows from and to these ports can then be transported over the main routes. This diminishes the flow on the feeder service networks, which can reduce the costs of the feeder network. Ports can be visited both on one or more main routes and on a feeder route.

The method can be performed before or after the method to decrease the feeder network. When it is performed before reducing the feeder network, the exact feeder costs are not yet known. Therefore, in this case only the decrease in feeder (un)loading cost are seen as cost reduction, where also the capital, operating and fuel costs are considered when the feeder network is already decreased.

Algorithm
The next algorithm gives a brief description of the method used to investigate whether ports should be added to main routes or not. In this algorithm, changes are only made in step 6. So, changes in other steps of the algorithm are only temporarily. When the algorithm returns to a previous step, the changes are undone. After the description of the algorithm, some steps of the algorithm are explained in more detail.

1. Consider a main route and determine the clusters that are visited on that main route.
2. Consider one of those clusters.

3. Determine which (noncentral) ports that belong to the cluster are not yet visited on the considered main route.
4. Determine the consecutive port combinations on the main route for which at least one of the ports belongs to the cluster.
5. Repeat the following steps as long as not all combinations of noncentral ports and consecutive port combinations are considered.
   (a) Select a combination of a noncentral port N and a port combination (P_1, P_2).
   (b) Remove port combination (P_1, P_2) from the main route and add the combinations (P_1, N) and (N, P_2) to the route.
   (c) Determine the new loads on the main route and on the feeder service serving port N after reallocating as much cargo from and to port N as possible to the main route.
   (d) Determine the increase in profit obtained by adding port N between ports P_1 and P_2 at the main route. If the increase in profit is higher than the highest increase in profit obtained earlier, save the new highest increase, the considered cluster and main route and ports N, P_1 and P_2.
6. In this step a port is finally added to a route, however three possible methods are distinguished.
   (a) Consider first all clusters and all routes and add thereafter the most profitable port to the main route.
      i. Return to step 2 as long as not all clusters are considered.
      ii. Return to step 1 as long as not all routes are considered.
      iii. Add the most profitable port at the most profitable place to the main route if the increase in profit is bigger than 0.
      iv. If a profitable change is made in step 6(a)iii, return to step 1, else stop.
   (b) Consider all clusters, add the most profitable port to the main route and consider thereafter all routes.
      i. Return to step 2 as long as not all clusters are considered.
      ii. Add the most profitable port at the most profitable place to the main route if the increase in profit is bigger than 0.
      iii. Return to step 1 as long as not all routes are considered.
      iv. If for at least one route a profitable change is made in step 6(b)ii, return to step 1, else stop.
   (c) Add the most profitable port to the main route and consider thereafter all clusters and routes.
      i. Add the most profitable port at the most profitable place to the main route if the increase in profit is bigger than 0.

ii. Return to step 2 as long as not all clusters are considered.

iii. Return to step 1 as long as not all routes are considered.

iv. If for at least one of the clusters a profitable change is made in step 6(c)i, return to step 1, else stop.

Uniquely defined clusters
The algorithm describes the main idea of the method used. However, the algorithm would become too complex if all details are included. Therefore, for each step, the details will now be discussed. First of all, note that each cluster can be visited twice on a route, so steps 2 and 3 have to be clarified. If a cluster is visited twice on a route, the visits are assumed to be to different clusters. So, a distinction is made between the cluster when it is visit on the eastbound part of the route and the cluster when it is visited on the westbound part of the route. So, each cluster that is visited on a route is unique for the route. Thus, when in step 3 is determined which ports of the cluster are not yet visited on the main route, only the part of the route where the considered cluster is visited is considered.

Thereafter, in step 4 all consecutive port combinations on the main route for which at least one of the ports belongs to the cluster are determined. Again, the cluster is unique on a route, so only the port combinations on the westbound part or on the eastbound part of the route (dependent on the location of the cluster) are considered.

Determine new loads
In step 5c, the new loads on the main route and the feeder service visiting N have to be determined. The idea is that as much cargo from and to port N as possible is reallocated from a feeder service to the main route. The amount of cargo that can be reallocated is first of all restricted by the total amount of cargo from/to port N that is present on the ship. Furthermore, it depends on the free capacity of the ship on the additional legs. To determine how much cargo can be reallocated according to the free capacity of the ship, first the position of the inserted port N with respect to the center of the cluster has to be determined.

Two situations can be distinguished: the central port of the cluster is already visited when port N is visited on the main route, or the central port of the cluster has still to be visited when port N is visited. Figure 6.1 shows the two possibilities. In the figures, only the central ports of the clusters and port N are considered, but all conclusions that will be drawn, will also holds when more ports are on the route.

Now, consider the left figure, where port N belongs to cluster C_1 and is visited after the central port of the cluster. In the original route, the ship visits first the center of cluster C_1 and directly thereafter the center of the cluster C_2. Thus, the cargo flows from and to port N are (un)loaded in the central port of cluster C_1. Now, call the flow between the two clusters F. The cargo flow with destination port N will be unloaded in the central port of C_1, so this flow is not included in flow F. On the other hand, the cargo flow with origin port N is included in flow F, because it is loaded in the central port of C_1.

When port N is added to the main route after the central port in the cluster, flows F_1 and F_2 have to be determined. The difference with the original situation is that the cargo flow from and to port N is now (un)loaded in port N in stead of in the central port of the cluster. Thus, in flow F_1 the cargo flow to port N is included where the flow from port N is not included.

Combining this with the flows included in flow F, it can be seen that

$$F_1 = F - N_{out} + N_{in},$$

where N_{in} is the amount of cargo flow unloaded in port N (flow with port N as destination) and N_{out} is the amount of cargo flow loaded in port N (flow with origin port N). In flow F_2 the cargo flow to port N is not included, where the flow from port N is included, so it holds that

$$F_2 = F.$$

Thus, the amount of cargo that can be loaded in port N, when looked at the free capacity is unbounded. However, the amount of cargo that can be unloaded in port N is bounded by

$$N_{in} \leq Cap - F + N_{out}.$$

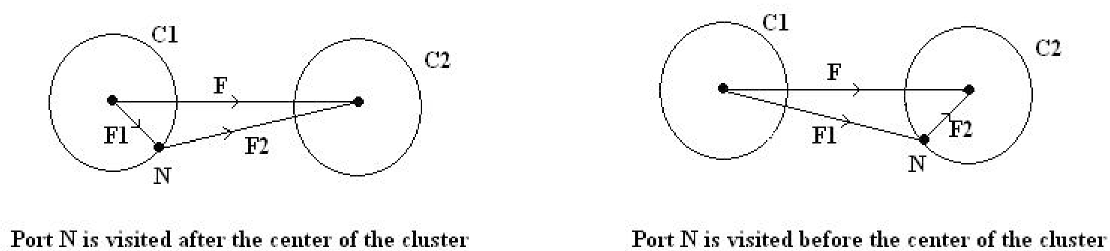

Figure 6.1: Example of the positioning of port N with respect to the central port of the cluster

The other situation is shown in the right figure. Now, port N belongs to cluster C_2 and is visited before the central port of the cluster. Again, the flow on the initial route between cluster C_1 and C_2 is denoted by F. In this case, the flow to port N is included in flow F, while the flow from port N is not included, because it will be loaded in the central port of cluster C_2. Now, consider flow F_1 between the central port of cluster C_1 and port N. In this flow, the cargo flow to port N is included and the cargo flow from port N is not included. Thus, in this case

$$F_1 = F.$$

The cargo flow to port N is now unloaded in port N, so this flow is not included in F_2. However, the flow from port N is already loaded in port N, so is included in F_2. Together with the flows included in F, it can be found that

$$F_2 = F - N_{in} + N_{out},$$

where N_{in} and N_{out} have the same definitions as above. Now, the amount of flow unloaded in port N is unbounded and the amount of flow that is loaded is bounded by

$$N_{out} \leq Cap = F + N_{in}.$$

Now, the amounts of flow (un)loaded in port N can be determined by taking the minimum of the amount present on the ship and the amount that can be (un)loaded according to the capacity. Thereafter, the new flows can be determined using the formulas for F_1 and F_2 given above. Furthermore, N_{in} and N_{out} can be used to update the flows on the feeder service visiting port N by subtracting the flows from the legs over which it should be transported. When no flows are loaded and unloaded anymore in port N on the feeder service, the port can be deleted from the feeder service.

Determine the increase in profit
In step 5d, the increase in profit is calculated. The increase in profit can be found by subtracting the increase in costs associated with the reallocation from the cost reduction. To determine the cost reduction, first check whether the feeder network is already reduced or not. When the method to reduce the feeder network is not yet performed, the cost reduction consists of the decrease in feeder handling costs obtained by reallocating flow from the feeder service to the liner services. When the feeder network is already reduced, the cost reduction can be found in the following way.

First, the new capacity of the feeder service has to be determined. The new capacity is defined as the smallest possible capacity that is higher than the load for each leg of the feeder service. The cost reduction is equal to the sum of the reduction is transhipment costs of loading flow from the main route to the feeder service, the reduction in (un)loading cost of the feeder service, the decrease in fixed cost (capital, operating and fuel) of the feeder service and the port cost saved on the feeder service (only when port N can be removed from the feeder service).

The additional costs incurred consist of the additional fuel costs incurred by sailing a larger distance, the additional (un)loading costs on the main route and the additional port cost incurred. When the increase in profit is determined, it is compared with the highest increase found earlier. If the new increase is higher, it is saved together with the main route, cluster, ports N, P_1, P_2 and the cargo flow loaded and unloaded in port N (N_{in} and N_{out}).

Add port to main route
In step 6 the real changes are made. This algorithm can be performed in three different ways. The way described in step 6a determines first for all clusters on all routes the increase in profit for all possible combinations before making a change. So, the best possible possibility is found and changed. This procedure is repeated until no profitable change can be made anymore. This method is very time consuming, because in each iteration all combinations have to be viewed.

Therefore, in step 6b the changes is already made after considering all possible combinations of one route. The method is repeated as long as a profitable change can be made in at least one of the routes. This method takes less time than the previous, but the performance will also be a bit worse.

Finally, in step 6c a method is described in which the change is already made after considering all possibilities of one cluster on one route. As long as a profitable change can be made for at least one cluster on a route, the method is repeated. This method will take the least time, but will also lead to the worst results. Therefore, a tradeoff has to be made between performance and computational time.

6.4.2.1 Comparison between the three insertion methods

In this section, the three methods that can be used to add a port to the main route are compared. The performance will be measured based on the computational time and a profit dependent measure. These measures are the same as the measures used in section 5.4.

In this section method A is the method in which a change is made after considering all clusters on all routes, method B is the method in which the change is already made after considering all clusters on one route and in method C the change is already made after considering one cluster on one route.

Table 6.2: Performance of the three methods that can be used to add ports to the main routes

		Method A	Method B	Method C	Random
10 clusters	SSD (10^{-6})	51.456	28.018	92.009	54493,778
	ART (s)	65.423	17.500	8.083	-
12 clusters	SSD (10^{-6})	10.226	27.493	29.401	44422,041
	ART (s)	60.325	17.250	7.773	-
15 clusters	SSD (10^{-6})	6.777	16.857	29.982	66310,873
	ART (s)	42.381	13.564	5.239	-
Total	SSD (10^{-6})	0.119	0.212	0.320	403,298
	ART	56.043	16.105	7.031	-

In table 6.2, the sum of squared deviations (SSD) between the selection probability of networks obtained when methods A, B and C are used and the selection probability of the networks when the optimal profit is used, and the average running times (ART) of the methods are given for three different number of clusters. The overall sum of squared deviations are obtained in the same way as in section 5.4. Furthermore, in the last column the sum of squared deviations between random selection and the selection probabilities obtained by using the optimal profit of the networks, is again given.

From table 6.2, it can be seen that method A has the smallest sum of squared deviation when 12 or 15 clusters are used, while in case of 10 clusters, method B has lowest sum of squared deviations. Method C has for all three different number of clusters, the highest sum of squared deviations. Overall, method A has the smallest squared deviation and method C the highest. However, the differences are very small (the sum of squared deviations is almost always more than 1000 times larger when random selection is used).

On the other hand, the running times are for each category highest for method A and lowest for method C. Method A needs on average about 8 times as much running time as method C. This number is about the same for each category. Method B performs both mediate in the deviation measure as in running time. However, method C is in each category more than two times faster. Because the method in which ports are added to the main routes has to be executed many times, running time is a very important measure for this method. Therefore, it is chosen to use method C in the overall approach used in this thesis. Thereafter, the other two methods can be used to improve the obtained profit of the best solution found with this approach.

6.4.3 Delete unprofitable demand

For some port combinations, the revenue of transhipping one TEU from the origin port to the destination is less than the handling costs incurred when transshipping this unit. To determine these port combinations, it is assumed that all demand is transshipped directly from the origin cluster to the destination cluster on the main route. Then the handling costs incurred when transshipping one TEU consist of

- cost of loading one TEU to a feeder ship in the origin port (only if the origin port is not the central port of a cluster)
- cost of unloading one TEU from a feeder ship in the central port of the origin cluster (only if the origin port is not the central port of a cluster)
- cost of loading one TEU to a liner ship in the central port of the origin cluster
- cost of unloading one TEU from a liner ship in the central port of the destination cluster
- cost of loading one TEU to a feeder ship in the central port of the destination cluster (only is the destination port is not the central port of a cluster)
- cost of unloading one TEU from a feeder ship in the destination port (only is the destination port is not the central port of a cluster).

Now, the port combinations for which the handling costs are higher than the revenue can be determined. When this demand is served directly on a main route, it is profitable, so it does not have to be removed. However, when it is served using a feeder service, it is unprofitable and has to be removed.

6.5 Evaluation

The aggregation process is needed when the size of the problem instances is large, because otherwise the model will become too time consuming. Problem instances with up to 15 ports can be solved in reasonable time, so at most 15 clusters are allowed in this thesis. Therefore, research question 5 can be answered positively. However, the structure of the problem does not change when it is decreased into a smaller problem. Therefore, the smaller problems can still not be solved using only mathematical programming techniques, so research question 5a has to be answered negatively. However, the cargo allocation model can now be used to solve the cargo-routing problem of a smaller problem.

After the cargo allocation model is solved with the clusters as input, the output data have to be disaggregated in individual port data. Thus, now research question 5b is answered. The disaggregation process cannot be done in a way that is guaranteed to be both optimal and with a reasonable computational time. Therefore, heuristic methods are used to disaggregate the cluster data in individual port data. Thereafter, some other heuristics are used to improve the disaggregated results. Because all heuristic methods are somehow related to each other and the quality of the results of one method thus depends on the quality of the input obtained by the other methods, it is very hard to perform any of them in an optimal way. However, the heuristics used in the disaggregation process and improvement steps can be used to convert the solution to the initial problem size.

Finally, a genetic algorithm based method is used to change the route network for which the cargo allocation model has to be solved again in order to find the optimal network. Then, the steps are repeated until a certain stopping criteria is met. This stopping criteria will be defined as a number of iterations. Next an overview of the overall approach used in this thesis is given.

1. Preprocessing
2. Aggregation
3. Designing an initial liner shipping network
4. Iterate the following as long as the stopping criteria is not met
    (a) Cargo allocation algorithm
    (b) Disaggregation
    (c) Improvement steps
        i. Add ports to main route
        ii. Delete unprofitable demand
        iii. Reducing the feeder network
            A. Reducing the size of the feeder network
            B. Exchanging a port between two feeder services
            C. Comparison
        iv. Add ports to main route
    (d) Genetic algorithm based method

The order of the improvement steps is not yet discussed, so it will now be explained. When the feeder network is reduced, it is important that as less flow as possible has to be allocated to a feeder service. Therefore, as many flow as possible has to be reallocated to the main routes before the feeder network is reduced. Thus, first the method to add ports to the main route has to be performed. Furthermore, the method that deletes unprofitable demand also reduces the flow on the feeder network. Thus, this is also performed before the feeder network is reduced. After the feeder network is reduced, the costs of the feeder services are known. Then, it is earlier profitable to add ports to the main route. Thus, this method should again be performed to increase the profit.

In the overview stated above, two steps that are not yet considered are mentioned. The method used to design an initial route network is described in the next chapter. Thereafter, the genetic algorithm based method is explained in chapter 8. In these chapters, research question 5c will be further investigated.

Chapter 7

Designing an initial liner shipping network

In this chapter the method used to create an initial liner shipping network is explained. Therefore, this chapter is related to the following research question:

5. (c) If the smaller problems still cannot be solved using only mathematical programming techniques, can these problems then be solved using a combination of mathematical programming techniques and heuristics or using only heuristics?

The liner shipping network is one of the inputs needed for the cargo allocation model. In first instance, the network is developed at random. In this thesis it is assumed that the ships call the port clusters in a fixed, predetermined order.

So, first the determination of the route order will be discussed. Thereafter, it is explained in which way the initial routes are generated. When the routes are known, the optimal speed of the ships on the routes can be determined. This will also be explained in this chapter.

7.1 Determine route order

After the aggregation process, the clusters that are input of the cargo allocation model are known. The liner shipping network consists of routes made between these clusters. It is assumed in this thesis that the clusters are always visited in the same order. The order is based on the geographical location of the cluster. The route order is determined in the following way.

Add nearest port cluster
First, determine which pair of clusters have the largest distance between each other. The cluster of this pair that belongs to the first region, is defined to be the first cluster in the order and is called C_c. The first region becomes the current region R_c and the second region becomes region R_n. The next cluster can each time be found by finding the cluster that belongs to region R_c or R_n and is nearest to cluster C_c. This cluster is the new C_c. If C_c belongs to R_c, then R_c and R_n remain unchanged. However, if C_c belongs to R_n then save all

clusters that belong to region R_c and are not yet allocated to the route order. Furthermore, set $R_c = R_n$ and let R_n become the region that follows region R_c. Repeat these steps until all regions are considered.

Add unallocated ports
Now, the unallocated clusters are considered one by one. For each cluster, determine at which location in the route order it can be added in such a way that the additional distance of the route is increased as least as possible. The additional distance can be calculated in the following way. When cluster C is added between clusters A and B, the additional distance becomes

$$Dist(A,C) + Dist(C,B) - Dist(A,B).$$

When all unallocated ports are also allocated to the route order, the route is reflected, so that the last port becomes equal to the first port. Now, the order in which the clusters are called on each route is determined. Because each cluster (except the middle cluster) appear twice at the route order, it can also be called twice.

7.2 Generate initial routes

This section describes the method used to generate initial routes. First, the number of routes in the network has to be determined. This is done by generating a random integer number between the minimum and maximum number of routes in a network. Thereafter, for each route in the network, a cluster is called with a certain probability.

When the method described in 5.4 is used, the most profitable routes are already selected from the route set in the algorithm. Therefore, it is less important to vary the number of routes in the initial networks. Thus, when the method of 5.4 is used, a constant number of routes are generated in each network.

Random initialization
Denote the probability that a port cluster is called on a route as p. For each cluster, generate a random number between 0 and 1. If the random number is less than or equal to p then the port cluster is visited on the route. If the random number is larger than p, the cluster is not called on the route. Finally, generate for each route randomly a capacity of the ship that will serve this route.

The value of p influences the length of the generated routes. Therefore, the value of p is varied to obtain routes of different lengths. In the overall model of this thesis, the value of p will be varied between 0.3, 0.4, 0.5 and 0.6 . In chapter 10, the value of p will each time be given.

Make the routes feasible
The routes obtained using the above method are not always valid routes. The routes have to satisfy three conditions to be valid. The first condition is that the beginning cluster of each route should be equal to the end cluster, so that a round tour is made. Therefore, it is checked whether this is satisfied. When this is not satisfied, the beginning or end cluster is adjusted, so that this condition is met.

The second condition is that the two middle clusters of the routes should be unequal, because otherwise the same cluster is visited twice in a row. This condition is also checked for each route and when it is violated, one of the middle clusters is removed.

The last condition is that the route length is at least equal to the minimum route length. If this condition is violated for a certain route, this route is deleted.

Using the above procedure a network is obtained with a random number of valid routes. This network can be used to run the cargo allocation model and obtain the different flows. Later on, the networks will be changed using a genetic algorithm based method, so that better networks are constructed.

7.3 Determine optimal speed

When the routes and capacities of the liner ships are known, it is possible to determine the optimal speed of the liner ship serving a certain route. In this section, the method to determine this optimal speed will be explained.

Consider a route of the route network and the capacity of the liner ship used to serve this route. Now determine the route durations in weeks when the ship sails at minimum and maximum speed. Determine the costs of sailing at minimum speed by adding the fuel costs to the capital and operating cost. Save the total costs and the speed. Thereafter, reduce the number of weeks with one as long it is larger than the number of weeks needed to sail the route at maximum speed. Determine the optimal speed when sailing the route in the new number of weeks. Using this speed, calculate the new capital, operating and fuel costs. If the total costs are lower than the saved costs, replace the saved costs by the new total costs and the saved speed by the new speed.

The saved costs and speed at the end of the procedure are the minimum costs and the speed for which these costs are obtained. So, the saved speed is the optimal speed for the route. Repeat the above procedure until all routes of the route network are considered.

7.4 Evaluation

This chapter describes the method used to generate initial route networks. Now, it is possible to generate an initial route network using the heuristic method described in this chapter and solve the corresponding cargo-routing problem using the cargo allocation model described in chapter 5. Therefore, research question 5c is already partially answered. This research question will be further investigated in the next chapter.

The initial route networks are needed as input of the genetic algotithm based method that will be described in the next chapter. For each initial route network, the profit will be determined using the methods described in chapters 5 and 6. Then, the genetic algorithm based method will allocate a selection probability to each network. Thereafter, networks are selected using these probabilities and changed.

In chapter 6 an overview of the model used in this thesis is given. One of the steps in this overview is 'Designing an initial liner shipping network'. A more detailed overview of this step is given below.

1. Determine route order
2. Generate initial routes
3. Determine optimal speed

Now, the only step that has to be clarified in the overview of chapter 6 is the genetic algorithm based method. This method will be explained in the following chapter.

Chapter 8

Genetic algorithm based method

In this chapter, research question 5c will be further investigated and answered. This research question is:

5. (c) If the smaller problems still cannot be solved using only mathematical programming techniques, can these problems then be solved using a combination of mathematical programming techniques and heuristics or using only heuristics?

The genetic algorithm based method needs a set of route networks as input. The number of networks in the set depends on the parameter settings. The initial route networks can be constructed using the method described in the previous chapter. When the initial network set is generated, the genetic algorithm based method will be used to change the networks. In this method, existing networks are combined to generate new, possibly better, networks. Thereafter, the profit of the new networks is determined. The idea is that in each iteration the performance of the networks is improved. The new profit can be determined by solving the (extended) cargo allocation model for the new networks. However, because it can become very time consuming to repeatedly solve the (extended) cargo allocation model, another method is used to determine the new profit for a fixed number of iterations i. Thereafter, the cargo allocation model is once again solved.

So, the method consists of two steps that are performed after each other. In the first step a new network is generated. This step uses elitism, selection, crossover and mutation. The elitism step ensures that the performance of the best network cannot decrease in the next iteration. In the selection step, networks are selected based on their performance. These selected networks are used in the crossover and mutation steps where they are combined and changed to obtain new networks. The second step is to determine the profit of the new network. In this chapter these aspects of the method are explained in more detail.

8.1 Background

Genetic algorithms are first formally introduced in Holland (1975). Genetic algorithms are based on biologic evolution and on the survival of the fittest principle. The survival of the fittest principle determines which members of a population survive and biologic evolution ensures that the genes of their offsprings are mixed and combined (Holland (1992)). One of the big advantages of genetic algorithms in comparison to gradient-based optimization techniques is that they can find the most promising areas in the search space. These areas are investigated in more detail, because an increasing number of individuals of the population will be produced in these regions after each iteration. In general, genetic algorithms avoid being trapped in local optima and get closer to the global optimum in comparison to other methods.

In Karray and de Silva (2004) genetic algorithm operators are described. The most common operators are selection, crossover and mutation. The selection operator is used to select the individuals that are used to reproduce new individuals for the next generation. Examples of selection operators are elitism in which the best individuals are copied unchanged to the next generation, the ranking model in which each individual is ranked based on its fitness value and individuals are selected according to these ranks and the roulette wheel procedure in which each individual is assigned a selection probability based on its fitness value and selection is based on these probabilities. In the crossover operator, two parents are combined to form two children in the next generation. The most common crossover operator used is n-point crossover in which n points are randomly selected and the genes of the parents between these points are exchanged and uniform crossover. Finally, mutation can introduce completely new individuals in a population by randomly changing some genes of an existing individual.

8.2 Design a new route network

One of the steps in the genetic algorithm based method is to design a new route network. When the new route network is constructed, the profit of the network has to be determined. However, a difference occurs in the method used to determine the profit when it is considered in the genetic algorithm based method than when it is determined by only solving the cargo allocation model. Therefore, the method to construct the networks is also different in both cases. When the profit will be determined in the next step of the genetic based method, only the elitism, selection and route crossover operators are used to construct a new network. On the other hand, when the cargo allocation model is used to solve the model, all operators are used. In this way, more individual routes in a network can be changed, so new routes are designed.

8.2.1 Elitism

The first step in the genetic algorithm based method is the elitism step. In the elitism step the best route network(s) of the current iteration are selected. These network(s) are unchanged placed in the network set of the next iteration. Elitism ensures that the performance of the best network in the next iteration cannot be decreased in comparison to the best network in the current iteration. The number of networks that are selected is one of the input parameters of the method.

8.2.2 Selection

In the genetic algorithm based method, networks are selected based on their performance. The selection step can be done in several ways. In this thesis the roulette wheel selection method is used to select the networks. In the roulette wheel selection method, a selection probability is assigned to the route network in the set based on their performance. Thereafter one of the networks is selected based on the selection probability.

First, the selection probabilities have to be determined. The selection probability of a route network equals the fraction of the profit of the route network compared to the sum of the profit of all networks in the network set. Assume that N is the number of route networks in a network set. So, the probability p_n of selecting network $n \leq N$ from the route set can be calculated by

$$p_n = \frac{Profit_n}{\sum_{m=1}^{N} Profit_m}.$$

When one of more of the networks in the set have a negative profit (loss), the highest loss obtained by a network in the set is added to the profit of all networks in the set before the selecting probabilities are calculated.

Next, for each $n \leq N$ the cumulative probability cp_n is calculated by

$$cp_n = \sum_{m=1}^{n} p_m.$$

Then a random number $rand$ between 0 and 1 is generated. Based on this random number $rand$, a network is selected. This is done using the following rule. Network $n \leq N$ is selected if $cp_{n-1} < rand \leq cp_n$, where $cp_0 = 0$.

The selected network will be used in the crossover or mutation step.

8.2.3 Crossover

When two networks are selected, the crossover operator can be used to recombine these two networks into two new networks. Two different crossover methods are considered in this thesis, uniform and route crossover. Next, these crossover methods will be explained.

Uniform crossover
In the uniform crossover methods, two completely new route networks are created. First, two existing networks are selected. Each network consists of $R\,(2C-1)$ 0/1 elements, where N is the number of routes in a network and C the number of port clusters found after the aggregation phase. So, $2C-1$ are the possible stops of a ship on a route. When the element corresponding to port cluster $c \leq 2C-1$ and route $r \leq R$ has value 1, port cluster c is called on route r.

The idea of the uniform crossover method is that for each $(r, c)\,, r \leq R, c \leq 2C-1$ a random number $rand$ between 0 and 1 is generated. When $rand \leq 0.5$, then the value corresponding to r and c in the first selected route network is copied to the first new route network and the value of the second selected route network is placed in the second new route network. On the other hand, when $rand > 0.5$, in the first new route network, the value corresponding to r and c from the second selected route network is placed and the value of the first selected route network is copied to the second new route network.

Finally, a capacity has to be allocated to each route in the new networks. This is also done by generating a random number $rand$ between 0 and 1. When $rand \leq 0.5$ the capacity corresponding to the first selected route is allocated to the route in the first new route network and the route in the second new route network will be given the capacity of the second selected route. When $rand > 0.5$, the capacity allocation is just the other way around.

Using this procedure, the two new route networks will probably contain one or more infeasible routes. Therefore, the routes have to be made feasible. This can be done in the same way as explained earlier in the route initialization.

Route crossover
The other crossover method that can be used is the route crossover. This method does not change existing routes, they are only exchanged between route networks. The advantage of this method is that cargo allocations on a route are still feasible in the new route network.

In the route crossover method, routes are thus exchanged between networks. Therefore, first a random number $rand$ between 0 and the number of routes in a network R is generated and rounded to the nearest integer that is equal to or larger than the generated number. Then all routes $r \leq rand$ of the first selected route network are placed in the first new network and all other routes of the first selected route network are copied to the second new network. For the second selected route network, the routes $r \leq R$ are copied to the second new network and the other routes to the first new network. Note that the capacity used on a certain route is never changed in this step. So, when a route is placed in the first new route network, the capacity corresponding to this route is also placed in the first new network. The same holds for the second new network.

All routes that occur in the new route networks that are created using the route crossover method are always feasible, because they are unchanged according to the routes in the current iteration. Therefore, the routes do not have to be checked on feasibility.

8.2.4 Mutation

Finally, the mutation method changes the value of some elements. When a route network is selected, some elements corresponding to a route and a port cluster are selected at random. The selected ports are added to the route, when they are not visited on the current route. On the other hand, when the ports are visited on the current route, they are deleted from the route. Furthermore, the feasibility of the route has to be checked, because the mutation operator can make routes infeasible. When the routes become infeasible by the mutation operator, they are made feasible in the same way as explained in chapter 7.

Finally, the capacity of a certain route will be changed with a certain probability. The new capacity will then be randomly chosen from the existing capacities. When the capacity of the routes can also be changed, more feasible route networks will be considered. However, changing the capacity on a route can influence the allocation on the other routes in the same route network. This effect will also occur when the routes are changed, but the effect will probably be bigger when changing the capacity. Therefore, the probability of a mutation in the capacity is chosen to be small.

8.3 Determine the profit of the new routes

The genetic algorithm based method is not only used to create new networks that can be solved with the cargo allocation model. The first i iterations in which new networks are generated, only whole routes are exchanged between route sets. The capacity of the route is then also exchanged, so the cargo allocation of that route obtained by the cargo allocation model, is still valid in the new route set. This allocation can now be used to reduce the demand of the new scenario, so that a smaller problem has to be solved using the cargo allocation model. Therefore, the computational time of the cargo allocation model is reduced. This section will describe the method used to decrease the demand and determine the profit of the new routes.

Decrease demand and capacity
The cargo allocation as determined when solving the cargo allocation model in the main method, is known for each route in a route network. So, for each pair of port clusters, the satisfied demand in the network can be calculated. When the total satisfied demand between two port cluster is smaller than or equal to the demand between these port cluster, the satisfied demand is subtracted from the demand. Furthermore, the capacities are updated, so the capacity of each leg used to transport the cargo is reduced by the amount transhipped.

When the satisfied demand is larger than the demand, for each route, the length of the path between the two port clusters is determined. Thereafter, as much cargo as possible is allocated to the route with the shortest path. This cargo is subtracted from the demand and the capacity of the legs of the shortest path is reduced by this amount. The above steps are repeated until all demand is allocated.

Determine profit
Thereafter, the cargo allocation model is solved with the new demand and capacity values. Because the amount of demand is reduced in this situation, the computational time of the model will also be reduced. After the model is solved, the demand flows determined above are added to the flows and the new profit of the network can be determined.

The profit found in this way can be lower than the optimal profit of the network. The reason for this is that some flows are already fixed before the model is solved. In the optimal allocation it could be optimal to allocate these flows to other routes. However, because an optimal allocation of the route in another network is used, the difference between the found profit and the optimal profit will not be large.

8.4 Evaluation

Below, a short overview of the genetic algorithm based method described in this chapter is given. This overview is the explanation of step 'Genetic algorithm based method' in the description of the method used in this thesis given in chapter 6.

1. Repeat the following i times
   (a) Design a new route network
      i. Elitism
      ii. Selection
      iii. Route crossover
   (b) Determine the profit of the new routes
2. Design a new route network
   (a) Elitism
   (b) Selection
   (c) Crossover
      i. Uniform crossover with probability p
      ii. Route crossover with probability $1 - p$
   (d) Mutation

As can be seen in the overview, the genetic algorithm method consist of two parts. The first part is iterated for i times, where the value of i can be varied in different scenarios. In this iterated part, a new network is constructed using only elitism, selection and route crossover. In this way, the cargo allocation of the routes in the previous network can be used to decrease the size of the input of the cargo allocation model. This will result in a reduction of the computational time of the cargo allocation model. However, using this method, no new routes are constructed. Thus, this way of changing the route networks cannot prevent that the method will be stuck in a local maximum.

Therefore, after i iterations, the uniform crossover and mutation operators are used to construct new routes in a certain route set. Thereafter, these routes have to be made feasible. The new route networks can then be used to solve the (extended) cargo allocation model again. This is the next step in the overview given in chapter 6.

In the algorithm, two parameters are introduced i and p. The values of these parameters can be varied when executing the overall model. However, in the remaining of this thesis, constant values for these parameters are used. The number of iterations i equals 5 and the crossover probability equals 0.4.

In the previous chapter, research question 5c is already partially answered. Using heuristical methods and mathematical programming techniques, an initial network can be created and the corresponding cargo-routing problem can be solved. In this chapter, a method is provided that changes the networks using a heuristic method. Thus, research question 5c is now answered entirely.

Chapter 9

Upper bound and reference network

In this chapter, the following subquestions are considered:

6. Can a good upper bound on the profit be determined?
7. Which service network can best be defined as reference network that can be used to compare with other networks?

In the first section, a method to calculate an upper bound on the profit will be proposed. The second section describes the network that will be used as reference network.

9.1 Upper bound

An upper bound on the profit can be calculated by determining for each port combination the maximum profit that can be obtained. These maximum profits per port combination can be found by subtracting the minimum costs from the maximum revenue per port combination. Then, only demand between port combinations for which the maximum profit is positive will be satisfied.

Maximum revenue per port combination
The maximum revenue per port combination can easily be determined by multiplying the demand between the port combination with the distance and the revenue per unit per nm. The revenue per unit per nm depends again on the direction in which the demand is traveled.

Minimum cost per port combination
The costs per port combination consist of the cost of visiting a port, the fuel cost of sailing from the origin to the destination port, the capital and operating cost of the ship used to sail between the port combination and the handle cost of (un)loading the demand in the origin and destination port. The handling cost per port combination can be determined as the cost of loading in the origin port times the demand plus the cost of unloading in the destination port times the demand.

The other costs depend on the ship size and speed. A lower bound on these total costs is needed. The minimum cost between a port combination is obtained when the demand between the port combination is served directly and the most cost efficient ship and sailing speed are used. Therefore, it is allowed that a non integer number of ships is used to satisfy the demand. Furthermore, the capital and operational costs are not calculated for an integer number of weeks, but only for the time needed to serve the demand. To obtain a lower bound on the port costs, it is determined how many ships (with the largest size) are needed to serve all demand to and from the considered port. The minimum number of ships needed equals the minimum number of port visits needed to serve all demand, so this number can be multiplied with the cost of a port visit. The lower bound on the total port costs can then be obtained by summing all lower bounds of the individual port costs.

For each port combination, the total capital, operating, fuel and port cost are calculated for each combination of ship capacity and sailing speed. Thereafter, the minimum value is selected and the total handling costs are added to obtain the minimum total cost per port combination.

Upper bound on the profit
Now, the profit per port combination can be calculated by subtracting the total cost per port combination from the total revenue per port combination. In the optimal situation, only demand between port combinations for which the profit is larger than 0, is satisfied. Therefore, the upper bound on the total profit can be found by summing the profit per port combinations for all port combination for which this profit is larger than 0.

However, an imbalance will be found in the number of ships needed to satisfy the demand in the east and west bound direction, because the demand differs per direction. This means that in some ports more ships will enter than leave, while in other ports more ships will leave than enter. Therefore, in a feasible solution additional costs have to be made to sail these ships back from their destination ports to their origin ports. However, the ships have different sizes, so it is hard to combine origin and destination ports for these ships. Thus, it is clear that in reality more costs will be incurred than found in this calculation. The gap between the best found solution and the upper bound can therefore become relatively large.

9.2 Reference network

In this section, a reference network will be defined to which the best obtained networks (i.e. the networks with highest profits) can be compared. This will give some additional information on the performance of the found networks.

The original Maersk route network, on which the data is based is used as reference network. The network consist of nine routes, which can be found in table B.1 in appendix B. On each route a few ships with different capacities are sailing to serve the demand. In table B.2 in appendix B the different ships and their capacity are given for each route. In this thesis, a route is served by ships of the same size. Therefore, it has to be determined which size will be used on each route. First, the average capacity on each route can be determined. These average capacities on each route are given in table 9.1.

However, in this thesis all capacities are multiples of 1000 TEU, while the average capacities of the routes in the Maersk network are not multiples of 1000 TEU. Therefore, the average capacities have to be transformed to multiples of 1000 TEU. This can be done in three different ways: the capacities can be floored, rounded or ceiled. When the capacities are floored, the new capacity takes the value of the largest multiple of 1000 TEU that is smaller than the average capacity. The rounded capacity is the nearest multiple of 1000 TEU and the ceiled capacity takes the value of the smallest multiple of 1000 TEU that is larger than the average capacity. The floored, rounded and ceiled capacities can also be found in table 9.1.

Table 9.1: Capacities on the routes of the Maersk network

	Capacity			
	Average	Floor	Round	Ceil
AE1/AE10	8365	8000	8000	9000
AE10/AE1	8316	8000	8000	9000
AE2	8439	8000	8000	9000
AE3	6504	6000	7000	7000
AE6	9086	9000	9000	10000
AE7	13643	13000	14000	14000
AE9	6474	6000	6000	7000
AE11	8231	8000	8000	9000
AE12	6621	6000	7000	7000

The cargo allocation model is solved for all three methods to transform the capacities. Furthermore, a procedure is introduced to optimize the capacity per route. This procedure starts with maximal capacity on each route. Then, the cargo allocation model is solved and the maximum used capacity of each route is determined. The capacity on each route is then reduced to the smallest possible capacity that is enough to cover all flows on the route.

Thereafter, the capacity on the routes are decreased one by one and each time the new profit is calculated. When all routes are considered, the capacity is decreased on the route where it will lead to the highest increase in profit. This is repeated until the profit can not be increased anymore in this way. The obtained capacity in the last iteration is the optimal capacity.

Finally, the demand between the port combinations is varied to investigate the effect of changes of the demand on the obtained profit. This is useful because demand is often not known on forehand. Therefore, it is desirable that the networks are not too sensitive to changes of the demand. The demand matrix is multiplied by 0.95 and 1.05 to this purpose.

9.3 Evaluation

In this chapter, a method is proposed to determine an upper bound on the profit that can be obtained. Thus, subquestion 6 is considered in this chapter. The upper bound can be obtained by determining the maximum possible revenue and minimum possible total costs. The upper bound on the profit can then be calculated by subtracting the costs from the revenue. The minimum costs are found when the demand between each demand pair is directly served with the most cost efficient ships. However, the demand differs in the different direction, so an imbalance between the number of ships needed in the east and west bound direction is found. It is hard to correct for this, because the ships can have many different sizes. Therefore, the highest possible profit that can be obtained from a feasible network, can be relatively far away from the upper bound. This has to be remembered when subquestion 6a is considered.

Therefore, a reference network is defined to which the other networks can be compared in order to answer subquestion 7. The Maersk network is used as reference network, because the data is based on this network. The ship capacities have to be transformed to make them feasible in the model. Furthermore, a procedure is proposed to optimize the ship capacity.

Chapter 10

Results

In this chapter, the results of the overall model will be presented. All results in this chapter are obtained using the data described in chapter 4, unless otherwise stated. In the first section, the results of the upper bound calculation are given. Thereafter, the results of the original Maersk route network on which the data is based, are described. Finally, the results of the overall model used in this thesis are given.

10.1 Upper bound on the profit

In this section, the results of the upper bound calculation on the profit is given. The method used to determine this upper bound is described in chapter 9. The main idea of the method is to consider all pairs of port combinations separately. For each pair an upper bound on the profit is determined by allocating the demand between the pair to the ship with the lowest cost. In this calculation, ships are allowed to be used fractionally. Furthermore, the optimal capital, operating and fuel costs are determined by considering the different sailing speeds and corresponding sailing times and fuel consumption. The upper bound on the total profit can then be found by summing all upper bounds of the individual port combinations. Note that the demand between port combinations for which the upper bound on the profit is negative, is not satisfied. Characteristics on the total costs can be obtained in the same way as the total profit. The results of this calculation can be found in table 10.1.

Table 10.1: Results of the upper bound calculation

Characteristics	
Profit in billion $	4.225
Revenue in billion $	7.634
Costs in billion $	3.409
Capital and operating cost in billion $	0.342
Fuel cost in billion $	0.763
Port cost in billion $	0.075
Handling cost in billion $	2.230
Percentage demand fulfilled	94.05

From the table it can be seen that the profit that can be obtained is at most $4.2 billion. However, note that the capital, operating, fuel and port cost are relatively small compared to the handling cost and revenue in this calculation. In the literature, it is often noted that about half of the total costs are incurred by fuel cost (see for example Notteboom (2006)). Thus, the capital, operating, fuel and port cost will probably be underestimated in this calculation.

The total handling cost can easily be determined, because they only depend on the total amount of cargo transported. On the other hand, the capital, operating, fuel and port cost also depend on the round tour time of the routes and the number of times a port is visited on a route. In a feasible network, both the round tour time in weeks and the number of port visits are integer numbers, while they are fractional in the upper bound calculation. This will result in a larger gap between the lower bound on these costs and the costs incurred in a feasible network.

Thus, the gap between the upper bound obtained using this calculation and the optimal feasible profit depends mostly on the gaps corresponding to the capital, operating, fuel and port cost. Because only one of the five cost components can be estimated well, the optimality gap is expected to become relatively large. Therefore, it is indeed useful to compare the networks also with a reference network.

10.2 Maersk network

This section describes the results of the original Maersk network. First, the results of the procedure used to optimize the ship capacity are given. Thereafter, the profits of the considered combinations of demand and ship capacity are given and finally, some additional characteristics on the best networks when the original demand is used, are given.

10.2.1 Optimizing the ship capacity

The procedure described in section 9.2 is used to optimize the ship capacities on the routes in the Maersk network. In this procedure, first the maximum ship capacity is allocated to each route. The optimal profit in this case is determined by solving the cargo allocation model. Thereafter, on each route the capacity that is minimally needed to satisfy all cargo flows is selected. This will be the initial network of the first iteration of the procedure. In each iteration, the ship capacity on a route is decreased and the new total profit is determined. This is done for all routes separately. Then, the network with ship capacities that result in the highest profit is selected as initial network for the next iteration. This is repeated as long as the highest profit exceeds the profit obtained with the initial network of the iteration.

The best ship capacities obtained using this procedure are given in table 10.2. The average ship capacities used on the real network are also given in this table.

From table 10.2 it can be seen that the optimal capacities on routes AE1/AE10, AE7, AE11 and AE12 are about the same as the capacities currently used by Maersk. Furthermore, in the optimal situation the capacity is decreased on routes AE10/AE1, AE3 and AE6. For routes AE2 and AE9 the capacity is increased. However, the real question is what the effect of optimizing the ship capacities is on the profit. This will be discussed in the next section.

Table 10.2: Optimal ship capacities for the Maersk route network

	Capacity	
	Real	Optimal
AE1/AE10	8365	9000
AE10/AE1	8316	4000
AE2	8439	12000
AE3	6504	4000
AE6	9086	8000
AE7	13643	14000
AE9	6474	12000
AE11	8231	9000
AE12	6621	7000

10.2.2 Effect of changes in ship capacity and demand

In this section the effect of changes in the ship capacity on the routes and in the demand between port combinations is investigated. Thereto, the cargo allocation model is solved for different combinations of ship capacity and demand. The profit obtained using the optimal capacities found in the previous section is compared to the profit obtained using the original ship capacities. However, the original capacities are not multiples of 1000 TEU as is required in the model. Therefore, the capacities have to be rounded to an integer multiple of 1000 TEU. The rounding can be done in three different ways: by rounding the capacities to the nearest multiple of 1000 TEU that is larger than or equal to the real capacity (ceil), by rounding the capacities to the nearest multiple of 1000 TEU (round) or by rounding the capacities to the nearest multiple of 1000 TEU that is smaller than or equal to the real capacity (floor).

Furthermore, the sensitivity of the route network to changes in the demand is investigated in this section. Thereto, the demand matrix used in this thesis is once multiplied by 0.95 and once by 1.05. In this way, three different demand scenarios are created. Thus, in total nine different situations are compared in this section. The obtained profit of the route networks in the different situations can be found in table 10.3. Because it is hard to compare the obtained profits when different demand input is used, in table 10.4 the percentage of demand delivered in each scenario is shown.

Table 10.3: Profit in billion $ of the Maersk network for different demand and ship capacities

	Capacity			
	Floor	Round	Ceil	Optimal
95% demand	1.566	1.547	1.543	1.635
100% demand	1.686	1.682	1.707	1.792
105% demand	1.790	1.801	1.853	1.930

First, the profit obtained using the three different rounded original capacities are compared. From table 10.3 it can be seen that the ceiled capacities results in the highest profit in case of normal and increased demand. Only in the case when the demand is decreased to 95%, using the rounded capacities results in a bit higher profit. Thus, the ceiled capacities give in

Table 10.4: Percentage demand delivered for different demand input and ship capacities

	Capacity			
	Floor	Round	Ceil	Optimal
95% demand	79.2	81.2	86.4	84.8
100% demand	76.2	78.5	83.2	81.6
105% demand	73.6	75.7	79.9	78.7

general the best results. Therefore, in the remaining of this thesis the ceiled capacities will be used in the reference network.

Furthermore, table 10.4 shows the percentage demand delivered for the rounded capacities. The ceiled capacities always lead to the highest percentage demand delivered, while the floored capacities always result in the lowest amount of demand delivered. This is quite logical, because the highest total capacity is obtained when ceiling the original capacities and flooring them will result in the smallest total capacity.

From table 10.3 it can further be seen that the optimal capacities will indeed result in the highest profit for all demand values. However, the percentage demand delivered is always higher for the original capacities. The increase in profit is apparently obtained by selecting more cost-efficient demand.

When decreasing the demand to 95%, the profit of the network with optimal ship capacities decreases with $\frac{1.792-1.635}{1.792} \cdot 100\% = 9.6\%$, while the profit of the network with ceiled capacities decreases with $\frac{1.707-1.543}{1.707} \cdot 100\% = 10.7\%$. However, when the demand is increased to 105%, the increase in profit is larger for the network with ceiled capacities: 8.5% against 7.7% for the network with optimal ship capacity.

The percentage demand delivered increases when the total amount of demand is reduced. The increase is 3.9% for both the reference network with ceiled capacities and the network with optimized capacities. However, when the total amount of demand is increased, the decrease in delivered demand is bigger for the network with ceiled capacities: 3.9% compared to 3.6% for the network with optimized capacities.

The ship capacities are optimized for the situation with normal demand. In that situation, the profit is increased from $1.707 billion of the reference network to $1.792 billion, an increase of almost 5%. Thus, by only optimizing the capacities on the routes, the profit can already be increased by almost 5%. In the next section, some additional characteristics of the reference network will be compared to the network with optimized capacities.

10.2.3 Comparison between the reference network and the network with optimized capacities

In this section, additional characteristics of the reference network will be given and compared to the network with optimized capacity. Table 10.5 shows these characteristics for both the reference network with given (ceiled) capacities and the network with optimized capacities.

From table 10.5, it can be seen that the increase in profit obtained when using optimized ship capacities is caused by decreasing the costs. More cost efficient ships are selected with

Table 10.5: Characteristics of the networks

	Reference network	Optimized capacities
Profit in billion $	1.707	1.792
Revenue in billion $	7.015	6.962
Cost in billion $	5.307	5.169
Percentage demand delivered	83.2	81.6
Capital and operating cost in billion $	1.150	1.114
Fuel cost in billion $	1.453	1.418
Port cost in billion $	0.189	0.189
Handling cost in billion $	1.972	1.935
Transhipment cost in billion $	0.544	0.514
Average utilization in %	63.1	65.4
Fleet size	91	91
Number of routes	9	9
Average number of port per route	16.4	16.4
Distance traveled in nm	191,754	191,754
Computational time in seconds	215.7	213.8

reduces the capital, operating and fuel cost. Furthermore, more cost efficient demand pairs are selected, which leads in less satisfied demand and thus less revenue and handling cost. The reduction in the revenue is smaller than the reduction in total costs, which results in an increase in profit. The utilization between two ports that are consecutively visited on a route is defined as the cargo on the ship between these port divided by the ship capacity. The average utilization is increased a bit when the optimized ship capacities are used, which means that the total capacity is used more effective in the network with optimized ship capacities. Finally, the port costs, fleet size, number of route, average number of ports per route and distance traveled are the same for both cases, because the same network is used and the computational time is therefore also about the same.

When the reference network is compared to the upper bound, it can be seen that the profit of the reference network lies almost 60% away from the upper bound. After, the improvement of optimizing the ship capacities, the profit is still almost 58% away from the upper bound. The revenue and handling cost are in the same order of magnitude in the Maersk network and the upper bound. However, the difference is indeed obtained in the capital, operating, fuel and port cost.

Tables 10.6 and 10.7 give some additional characteristics of the routes in the two networks.

The route characteristics of the reference network and the network with optimized capacities are very similar, because the same routes are included in the network. The only differences can be found in the ship capacities and average utilization. It can be seen that in general the average utilization is increased on routes for which the ship capacity is decreased. However, the average utilization is decreased for some routes in the network after optimizing the capacities. This can be explained in the following way. On a part of this route, the maximum capacity will be used, but not enough demand is available to obtain a high utilization on the whole route. Because the ship capacity is increased compared to the reference network, the utilization on

Table 10.6: Characteristics per route of the reference network

	Capacity in TEU	Speed in nm/hour	Round tour time in weeks	Distance in nm	Number of ports	Average utilization
AE1/AE10	9000	21.5	11	25,681	15	79.3
AE10/AE1	9000	21.5	11	25,020	18	71.6
AE2	9000	20	11	23,884	12	82.1
AE3	7000	20.5	10	18,827	22	50.8
AE6	10000	21	10	20,736	18	49.9
AE7	14000	20.5	10	21,774	13	49.0
AE9	7000	21.5	9	18,972	14	60.8
AE11	9000	20	10	18,686	20	62.5
AE12	7000	21.5	9	18,174	16	68.8

Table 10.7: Characteristics per route of the network with optimized capacities

	Capacity in TEU	Speed in nm/hour	Round tour time in weeks	Distance in nm	Number of ports	Average utilization
AE1/AE10	9000	21.5	11	25,681	15	82.4
AE10/AE1	4000	21.5	11	25,020	18	83.5
AE2	12000	20	11	23,884	12	77.3
AE3	4000	20.5	10	18,827	22	62.6
AE6	8000	21	10	20,736	18	57.9
AE7	14000	20.5	10	21,774	13	50.0
AE9	12000	21.5	9	18,972	14	56.6
AE11	9000	20	10	18,686	20	60.6
AE12	7000	21.5	9	18,174	16	59.1

these parts of the route will be decreased when the same demand is transported (because the utilization is defined as the flow divided by the ship capacity). This will result in a lower average utilization, while the same (or more) demand is fulfilled on the route.

10.3 Overall model

In this section the results of the overall model used in this thesis are given. First, the overall model is performed using different number of clusters and the obtained results will be compared. Thereafter, the obtained route networks will be used as input for a new run of the overall model. This will be used to determine the best networks for the different number of clusters. Finally, the best obtained network will be considered into more detail.

10.3.1 Different number of clusters

In this section the results of the overall model with different number of clusters are discussed. In the overall model, the first step is to aggregate the individual ports in a few different clusters. This clusters will be used as input of the cargo allocation model. After solving the (extended) CAM model, the flows between clusters are disaggregated into individual port flows. The number of clusters used in the model should be chosen carefully. When too many clusters are included, the model can become too slow, while too little clusters can lead to worse results, because the disaggregation process is not performed in an optimal way. Thereafter, ports are reallocated to the main routes and the size of feeder ships and routes are reduced to improve the obtained profit of the networks. Finally, networks are changed and the profit of the new networks are determined. This is repeated until a certain stopping criteria (in this case a certain amount of time) is met.

In table 10.8, the profits of the best networks obtained when executing the overall model with different number of clusters and different probabilities of adding ports to routes are given. The overall model is each time executed for about ten hours, whereafter the best network is selected.

Table 10.8: Profit in billion $ for different parameter settings

	Connection probability			
	0.3	0.4	0.5	0.6
10 clusters	2.385	2.307	2.323	2.326
12 clusters	2.246	2.277	2.285	2.353
15 clusters	2.250	2.194	2.253	2.011

From the table, it can be seen that the highest profits are obtained when 10 clusters are used. The highest profit of $2.385 billion is already an increase of 39.7% of the reference network. However, the profit is still 43.6% away from the upper bound. The obtained networks are used to design for each number of clusters a new initial set that can be used as input of the overall model. This is done by selecting from the best networks from the sets obtained when the model is performed with different probabilities of adding ports to routes. In this way, a high performance initial route network set is obtained. Thereafter, the overall model is executed again for each of the three different values of the clusters with these new intial sets. The results of the best networks obtained in this way are described in the next section.

10.3.2 Characteristics of the best networks

In table 10.9, the results of the best networks for the different number of clusters can be found. The table shows the profit, revenue and costs and some other characteristics.

Number of clusters

In table 10.9 some characteristics of the best networks obtained with ten, twelve and fifteen clusters are given. In this table, both characteristics of the main and feeder route networks are given. Again, the network obtained with ten clusters has the highest profit. This can be explained as follows. When less clusters are considered, less possible feasible routes exist, thus it is easier to find the best route network. The danger is that the feeder network becomes larger, which can result into a situation that does not represent the reality anymore. However, methods are used to decrease the feeder service and add ports from the feeder network to the main network to improve the performance. When the feeder network is larger, these methods

Table 10.9: Characteristics of the best networks for different number of clusters

	10 clusters	12 clusters	15 clusters
Profit in billion $	2.391	2.369	2.280
Revenue in billion $	6.959	7.072	6.595
Cost in billion $	4.568	4.703	4.315
Percentage demand delivered	81.2	84.1	76.7
Computational time in seconds per iteration	623.4	637.6	722.8
Main network			
Capital and operating cost in billion $	0.944	0.944	0.898
Fuel cost in billion $	1.249	1.253	1.191
Port cost in billion $	0.129	0.120	0.134
Handling cost in billion $	1.925	1.993	1.819
Transhipment cost in billion $	0	0	0.004
Total liner cost in billion $	4.247	4.309	4.045
Average utilization in %	62.9	65.2	66.7
Fleet size	61	59	56
Number of routes	6	6	5
Average number of port per route	16.5	15.3	20.6
Distance traveled in nm	12.8757	122.693	116.938
Feeder network			
Capital and operating cost in million $	65.925	72.375	51.225
Fuel cost in million $	59.650	59.958	46.434
Port cost in million $	9.360	9.360	8.840
Handling cost in million $	186.593	252.314	163.209
Transhipment cost in million $	0	0	0
Total feeder cost in million $	321.527	394.006	269.707
Average utilization in %	60	64.1	63.1
Fleet size	17	17	13
Number of routes	17	17	13
Average number of port per route	3.1	3.1	3.6
Distance traveled in nm	25.046	24.724	21.407

have more possibilities to improve the network. Overall, including ten ports in the initial main service network is optimal in this thesis.

Distance traveled

Note that the distance traveled for this network is higher than that of the networks with twelve and fifteen clusters for both the main and feeder routes. This can be explained in the following way. The main routes are constructed for only ten ports, which means that many ports are included in the feeder network. This will result in a higher distance traveled on the feeder routes. Then, ports that are included in the feeder network can also be added to the main routes. This increases the distance traveled on the main routes. However, the distance on the feeder network will only be reduced when a port can be deleted from the feeder network. A port can only be deleted from the feeder network if both the demand from and the demand to that port can be entirely served on the main route. In general, ports can not be deleted from the feeder service, so the distance traveled on both the main and feeder services are higher for cases with less number of clusters.

Round tour times
Furthermore, more ships are needed on the main service in the situation with only ten clusters. However, the capital, operating and fuel cost are not much higher or even lower than in the other situations. This indicates that more cost efficient ships are selected in the situation with ten clusters. Also on the feeder service, the capital, operating and fuel cost are relatively low compared to the number of ships when ten clusters are included. Thus, on the feeder service more cost efficient ships are chosen too.

Computational times
The computational times are given in seconds per iteration. An iteration consists of executing once the procedure as described in the overall model in chapter 6. Thus in one iteration, the profit of all twenty networks in the set are determined. Thereafter, the networks are changed using the genetic algorithm based method in which another iteration is included that is executed five times. In each iteration in the genetic algorithm method, the profit of all twenty networks is again determined. Thus, in one iteration of the overall model, the profit of 120 route networks is determined.

From table 10.9 it can be seen that the computational time per iteration is lowest for the situation with ten clusters and highest when fifteen clusters are included. In other words, the computational time increases with the number of included ports in the extended cargo allocation model. This could have been expected, because the size of the model increases with the number of ports and thus the computational time increases too. However, the methods that add ports to the main routes and decrease the feeder size become slower when less ports are included in the main services, because more possibilities have to be checked. Overall, the difference in computational time of the extended cargo allocation model has a larger influence than the difference in computational time of the other methods. Thus, the overall computational time decreases when the number of clusters decreases.

Number of routes
When the network obtained when ten clusters are included is compared to the reference network, the most important difference is the number of routes in the network. In the reference network nine routes are used, while in the new obtained network only six routes are used. The decrease in number of routes causes a decrease in the fleet size and distance traveled. This results in lower capital, operating, fuel and port cost on the main routes. Therefore, the costs on the main routes are decreased significantly. Because the feeder services are relatively cheap compared to the main services, the overall costs are also reduced.

Profit
The profit is increased with 40.1% compared to the reference network. This is an enormous increase, especially because most data used is based on the reference network. However, the profit is still 43.4% away from the upper bound. This is another indication that the costs in the upper bound caculation are probably underestimated. In the following section, some results of the individual routes in the best network will be described.

10.3.3 Best network

This section gives some additional characteristics per route of the best network found in this thesis. These results will be compared with the results of the reference network given in section 10.2.

Main network
The route characteristics of the main routes can be found in table 10.10. From this table it can be seen that the reduction in number of routes is captured by using large ships. All routes are sailed using ships with capacity at least 10000 TEU, while in the reference network also ships with a capacity of 7000 TEU are used. The distances and round tour times are about the same for routes in both networks. This indicates that the best obtained network covers in total less distance on its main routes than the reference network, as can indeed be seen in tables 10.5 and 10.9. In the best network, also a feeder network is included, which captures the difference in distance traveled.

Table 10.10: Characteristics per route of the main service of the best network

	Capacity in TEU	Speed in nm/hour	Round tour time in weeks	Distance in nm	Number of ports	Average utilization
M1	14000	20.5	11	21.515	23	74.0
M2	13000	21	11	23.943	18	68.4
M3	10000	21	10	22.825	12	41.5
M4	12000	21	10	20.116	19	67.0
M5	14000	21	10	22.666	13	49.4
M6	14000	20	9	17.692	14	63.1

Feeder network
The second part of table 10.11 shows the characteristics of the routes in the feeder network. The speed and round tour time in weeks are fixed for the feeder service, so they are left out the table. The number of ports included in a feeder route varies between two and four per route. When only two ports are included in a certain route, this means that the considered route is a direct feeder service from the central port in a cluster to another port in the cluster and back. The routes with three or four included ports are round tours in which each port is visited exactly once (except the central port, which is the start and end port of the route). The distance traveled per feeder route varies over the routes. For some routes, the maximum possible distance per route is almost reached. Examples are routes F14 and F16 for which the maximum possible distances are 2,376 and 2,706 respectively. The maximum distance is based on the maximum distance that can be sailed in a week when the time spent in ports are also considered.

Average utilization
Furthermore, for some routes the average utilization is lower than 50%. This are mostly routes that consist of only two ports, so for which a direct feeder service is used. An explanation can be that the port visited on such a route has a relatively large difference in demand allocated from and to that port. In this case, one direction of the service has a high utilization, while the other has a relatively low utilization. An other explanation can be that the port visited on the feeder route is also visited on at least one of the main routes. Then, it is possible that

Table 10.11: Characteristics per route of the feeder service of the best network

	Capacity in TEU	Distance in nm	Number of ports	Average utilization
F01	700	1.016	2	72.7
F02	350	664	3	85.8
F03	500	839	4	52.8
F04	2000	1.634	4	69.6
F05	500	464	2	43.8
F06	2250	1.841	3	64.2
F07	2500	2.099	4	61.0
F08	4000	1.059	4	47.0
F09	1500	1.270	4	58.0
F10	700	708	2	40.3
F11	700	577	4	66.8
F12	900	2.158	3	73.6
F13	2250	1.964	3	55.6
F14	350	2.347	4	58.9
F15	800	1.180	2	65.4
F16	500	2.638	3	51.4
F17	350	2.588	2	44.6

only demand from or to that port can be satisfied using only the main routes, so that the other demand has to be satisfied mainly on the feeder routes. The low average utilization on route F08 can be caused by the size of the feeder ship needed. Ships that sail on route F08 have a capacity of 4000 TEU. A feeder ship that is one size smaller has a capacity of 2500 TEU as can be seen from table A.5. Thus, it is possible that the maximum amount of capacity used is only a bit higher than 2500 TEU, which will cause a relatively low maximum and thus average utilization.

Included ports

Finally, in appendix E the routes of the best network are given in tables E.1 and E.2 and the number of times a port is visited on a main and feeder route is shown in table E.3.

The reference network only consists of a main route network, so all ports are at least once visited on a main route. However, from table E.3 it can be seen that not all ports are visited on a main route in the best network. First, the ports in Japan (Yokohama, Shimizu, Nagoya and Kobe) are not visited anymore on the main route. In China are many ports that are visited on a main route, but ships have to cross the ocean to visit ports in Japan. Because China is the turning point of the route, the crossing distance should be covered twice when ports in Japan are included in the main routes. Therefore, it is quite logical that the ports in Japan are only visited on the feeder services.

Furthermore, the ports in Northern Europe (Gothenburg, Aarhus and Gdansk) are not included in the main route network. A same reasoning as for the Japanese ports holds in this case. Ships turn in Rotterdam, Antwerp or Hamburg and adding one of the Northern European ports will result in additional distance that has to be covered twice.

The ports Izmit, Istanbul Ambarli, Odessa, Ilyichevsk and Constantza in Southern Europe are located in a cove, so that many additional distance have to be covered to visit these ports on the main routes. Again, it is then logical that these ports are not visited on the main routes, but are fully served by the feeder network, since smaller and cheaper ships are used on the feeder routes. The same reasoning holds for the ports Rijeka, Koper and Trieste in Southern Europe. These ports are also not visited on the main routes.

The last two ports that are only included in the feeder network are Fuzhou and Taipei. For these two ports another reasoning has to be made, because the additional distance that has to be covered to visit these ports is not very large (they are located near Xiamen en Kaohsiung, which are visited on some main routes). However, both Fuzhou and Taipei are relatively small ports. Therefore, the additional costs incurred by adding them to a main route, will probably not be covered by the decrease in feeder costs.

Order of the routes

Ports are mainly visited in geographical order on the routes in the best network found. However, sometimes small deviations from the geographical order are observed. These deviatons are caused by the way ports are added to the main routes. In general, the causes of the deviations can be divided in two categories.

The first category can be explained by considering for example route M1. This route serves on the westbound trip first Antwerp and thereafter respectively Felixstowe, Le Havre and Rotterdam. When these ports are visited according to geographical order, one would expect that the order would be: Le Havre-Felixstowe-Antwerp-Rotterdam. However, this order cannot be obtained in the model, because Le Havre and Felixstowe are part of a cluster with central port Rotterdam and Antwerp has its own cluster. When routes are added to the main ports, they can only be added directly before or after a port that belongs to the same cluster. To obtain the geographical order, Le Havre and Felixstowe have to be placed before Antwerp, which does not belong to the same cluster.

The other cause of deviations can be explained using route M4. On route M4 first Ningbo is visited and thereafter respectively Busan, Qingdao, Liangyungang and Shanghai. All these ports belong to the cluster with central port Shanghai. The geographical order would be Busan-Qingdao-Liangyungang-Shanghai-Ningbo. Thus, the location of Ningbo in the obtained route deviates from the geographical order. This can be explained in the following way. The method that adds ports to the main routes determines the best location to place a port on the existing route. The best location is defined as the location where the highest increase in profit can be obtained. The additional distance that has to be sailed is part of the decision, because additional costs are incurred when more distance has to be covered. However, the optimal place to add a port to the main route depends also on the reduction of the costs that can be obtained. A cost reduction can be obtained by reallocating cargo to the main routes, such that transhipment costs to the feeder services are saved. In chapter 6 it is seen that the amount of cargo that can be loaded in the added port on the main route is bounded when a port is placed before the central port of the cluster, while the amount of cargo unloaded from the main route is bounded when the port is visited after the central port of the cluster. Thus, although the optimal geographical location of Ningbo on route M4 would be after Shanghai, it can be more profitable to visit Ningbo before Shanghai when much cargo with destination Ningbo is on the ship.

10.3.4 Contribution of the individual methods

In this section, the contribution of the individual methods to the result is investigated. Thereto, the profit of the best network is recalculated while one of the methods is omitted from the model. The difference in the new profit and the best obtained profit will then be a measure of the contribution of the method that is omitted.

Table 10.12 gives the profits when one of the methods is omitted from the model. Furthermore, the difference compared to the profit obtained when all methods are included in the model is shown. The methods in which the feeder service network is reduced and unprofitable demand is deleted do not have a large influence in the obtained profit. The most important method is that in which ports are added to the main routes. However, this method is included twice in the model. Removing only one of the two times, does not have a large effect on the obtained profit, because most ports are then still added to the main route. When both methods are omitted, the decrease in profit is quite large (22.3%). Thus, the methods in which ports are added to the main routes has a significant contribution to the obtained profit, while the contribution of the other methods is negligible.

Table 10.12: Profit when one method is omitted from the model

Method	Profit in billion $	Difference in %
Reducing the feeder service network	2.391	0.01
Add ports to main route (first time)	2.354	1.59
Add ports to main route (second time)	2.369	0.10
Add ports to main route (both times)	1.858	22.32
Delete unprofitable demand	2.390	0.07

Chapter 11

Conclusion

In this thesis it is investigated how mathematical programming techniques together with heuristic methods can be used to solve the combined fleet-design, ship-scheduling and cargo-routing problem. Thereto, first a linear programming formulation (CAM model) is introduced that can be used to solve the cargo-routing problem to optimality. The results of this CAM model are compared with the results obtained using three different heuristic methods. In this comparison, different scenarios are considered, because some heuristic algorithms are expected to give better results is specific situations. In general, the best heuristic method performs more than 20% worse than the CAM model.

Thereafter, an extension of the CAM model is introduced in which the fixed costs of the routes in the network are also considered in the objective function of the linear programming model. Furthermore, an algorithm is proposed that can be used to select the most valuable routes in a given route network. Although the computational time of the CAM model is increased after this extension, the increase in obtained profit is considered to be more important in this situation. Therefore, the extension will be used in the overall model of this thesis.

However, the computational time of the (extended) CAM model is too high to solve repeatedly when all ports are included in the model. Therefore, an aggregation method is proposed that can be used to divide the ports in some clusters. The number of clusters is chosen based on the computational time of the model. In this thesis, ten to fifteen clusters are appropriate to work with. The design of the clusters is based on the geographical location of the ports.

After the results are obtained in clustered ports, the results have to be disaggregated again in individual port results. Some methods are developed and explained in this thesis. In these methods, a distinction is made between main services and feeder services. The feeder services are used to transport the cargo from the cluster centers to the other ports in the cluster. In first instance. only cluster centers can be part of the main service network. However, other ports are added to the main routes when this is profitable. Furthermore, the ship capacities on the feeder services are tried to decrease in the proposed methods.

The above methods can be used to determine the profit of a certain route network. A genetic algorithm based procedure is used to change existing networks into new networks, which can again be solved using above methods. In the genetic algorithm based procedure selection, crossover and mutation methods are used. The initial networks are generated at random and made feasible.

An overview on the overall model used in this thesis is given in chapter 6. Furthermore, a method to determine an upper bound is proposed and a reference network is introduced. In the upper bound calculation many of the costs (capital, operating, fuel and port costs) are underestimated. Therefore, the best obtained network will have a profit that is relatively far away from the upper bound. The reference network is the network used by Maersk with ship capacities ceiled to a feasible capacity in the model. Thereafter, first the ship capacity on the routes is optimized. This leads to an improve of almost 5% compared to the reference network. Furthermore, the effect of changes in the demand is investigated. The relative difference in profit after the demand is changed is about the same for both networks.

The overall model is performed with ten, twelve and fifteen clusters as input for the (extended) cargo allocation model. In all three cases, the model is executed for about ten hours, before it is stopped and the best network is selected. The scenario with ten clusters leads to the highest profit.

The best network found using the overall model gives an improvement of about 40% compared to the reference network. However, the profit is still 43% away from the upper bound, but, as mentioned earlier, the lower bounds on the costs used to determine the upper bound on the profit are probably underestimated. The most important difference with the reference network is the number of routes used. This number is decreased from nine to only six. Therefore, the capital, operating, fuel and port costs are also decreased.

The distance traveled on both the main routes and the feeder service routes is higher when ten clusters are considered than when twelve or fifteen clusters are included. When less ports are included in the (extended) cargo allocation model, more ports have to be served on the feeder service. Thus, more distance has to be travelled to visit all ports. The distance traveled on the main routes will probably be lower before the improvement steps are performed. However, when ports are added to the main routes, the total distance is increased. When less ports are included in the (extended) cargo allocation model, more ports can be added to the main routes. Many ports are added to more than one main route, so the increase in distance will probably higer when less clusters are used.

The reference network only consists of a main service network. Therefore, all ports are visited on at least one of the main routes. However, in the best obtained network not all ports are visited on a main route anymore. This can be explained in the following way. When the last ports before a turning port are noncentral ports in a network, the distance from the central port to these ports has to be covered twice when these ports are added to a main route. Thus, these ports can probably be better visited on a (cheaper) feeder route. Furthermore, some ports are located in a cove. The additional distance that has to be traveled to visit these ports can therefore become large. In this case, it is probably be more profitable to serve these ports on feeder routes instead of a main route. Finally, some ports have very little demand. For these ports, the additional costs of visiting these ports on a main route are higher than the maximum reduction in costs that can be obtained. Therefore, these ports can also better be visited on a feeder route.

The order in which the ports are visited on the main routes in the best obtained network correspond most of times to the geographical order. Some deviations can be found, because ports are afterwards added to the main routes. Two main reasons can be given that explain the existance of the deviations. First, in some cases, the geographical order cannot be obtained, because of the cluster design. Furthermore, the amount of cargo that can maximally be (un)loaded in a port that is added to a main route depends on whether the port is added before or after the central port of the cluster. Therefore, it can be more profitable to add a port after the central port of the cluster, even when the geographical order implies that the port should be added before the cenrtal port and vice versa.

Finally, the contributions of the individual methods used in this thesis are determined. Thereto, each time one of the methods is omitted from the model and the profit of the best obtained network is again determined. Then, it can be concluded that the method that adds ports to the main routes is the most important method in this thesis. When this method is omitted from the model, the profit is decrease with more than 22%. When the other methods are omitted, the decrease in profit is negligible.

Chapter 12

Discussion and further research

In this chapter the methods used in this thesis are further discussed and directions for further research are proposed.

First, it is important to have reliable data to obtain reliable results. Many data are unknown, so methods have to be derived to obtain these data. The distance and demand data are obtained from Lachner and Boskamp (2011). Although especially the demand data are very uncertain, they have developed a method that will probably give reasonable estimates of the demand between ports. The cost data are mostly obtained from Francesetti and Foschi (2002). Some of these costs have to be correct for inflation, but in general these data will be reasonably well chosen. However, in this thesis some additional ships are added to the set of possible ships. The costs of these ships are obtained by extrapolation on the costs given in Francesetti and Foschi (2002). The data become more unreliable in this case. However, because real data are unknown, better estimates are unavailable. In Lachner and Boskamp (2011) a beginning is made with constructing a standard data set. However, only a few ship sizes and speeds are considered. Therefore, it would be useful to extend this data set for future work.

In this thesis, a service network is constructed from scratch. This means that it is assumed that an infinite number of all different type ships is available. In reality, a liner shipping company will already have a given fleet. It is not likely that all ships allocated in the best obtained network are already available in the current fleet of the company. However, the method described can also be used when the fleet design is given on forehand. Thus, the result of the best network will not be valid anymore when a predetermined fleet has to be used, but the method is still valid.

The optimality of the heuristical methods in this thesis cannot be guaranteed. Furthermore, many methods depend on each other, which makes it hard to obtain the optimal solution. Therefore, an upper bound on the profit is determined in this thesis. The upper bound on the profit consists of the difference in the upper bound on the revenue and the lower bound on the costs. The upper bound on the revenue and the lower bound on the handling costs can be estimated well. However, the lower bound on the capital, operating, fuel and port costs cannot be estimated well. This is caused by the different sizes and sailing speeds of the ships. Therefore, it is recommended to perform further research on the construction of an upper bound on the profit.

In this thesis, the port and handling costs are assumed to be constant. However, in reality they may differ per port and ship size. The reason that these costs are not varied between ports and ship types is that no data are available about these costs. However, the model is able to handle variable port and handling costs. Furthermore, the port times can also be varied between ports and ship types in the model used in this thesis.

Furtermore, in this thesis no restrictions on the type of ships that can enter a port are imposed. However, some port do have such restrictions in reality. These restrictions mainly concern the size of the ships. In the model provided in this thesis, these restrictions cannot yet be incorporated. However, it would not be too hard to change the model in order to check these restrictions.

Only intra-regional demand is considered in this thesis, but it is possible to add also regional demand in the model. The idea behind the methods will stay the same when regional demand is included. The regional demand will not be considered in the methods discussed in the improvement steps in chapter 6. Because the revenue of the regional demand will be relatively low compared to intra-regional demand (because the distance between origin and destination is much smaller), this will hardly influence the performance of the methods.

Further, it is only succeeded in this thesis to formulate the cargo-routing problem as a linear programming problem. Furthermore, it is not succeeded to formulate the overall problem as a mixed integer programming problem. When a mixed integer programming problem of the overall problem is found, techniques like column generation or Benders decomposition can be used to solve the problem. When a larger part of the model can be solved to optimality, the performance of the overall model will probably become better. Therefore, it is recommended to perform further research on the formulation of the overall problem as a mixed integer programming problem.

The assumptions on the feeder services are stricter than that of the main services in this thesis. It could be further investigated what the effect will be when feeder ships are also allowed to sail with different speeds. Furthermore, it could be checked whether allowing the feeder routes to take longer than one week will improve the best solution found. However, because it is seen that the method used to decrease the feeder size is negligible in this thesis, it is expected that these extensions will hardly influence the best solution.

Furthermore, the initial network set is generated at random in this thesis. In first instance, it is expected that better initial networks will results in better final results. However, in chapter 10 the results of the overall model used in this thesis with random initial routes and with a high performance initial network set are given. The high performance initial set is obtained from the final networks obtained with the random generated sets. The difference in best obtained profit is very small between these two different route network sets. Therefore, it can be concluded that the performance of the initial set hardly influences the final results.

Finally, the genetic algorithm based method can be performed with different input parameters, like crossover and mutation probability. In this thesis, these probabilities are chosen constant. However, it could be investigated whether the performance of the results can be increased when these parameters are varied. Furthermore, it could be checked whether it would be profitable to change these parameters in an iteration of the model. Then, it is for example possible to start with very high crossover and mutation probabilities to explore a large part of the search area. Thereafter, the probabilities can be decreased to search a smaller part of the solution space more intensively.

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Appendices

Appendix A

Data

Table A.1: List of ports

Port name	Country	Region	Port name	Country	Region
Yokohama	Japan	Asia	Port Said	Egypt	Middle East
Shimizu	Japan	Asia	Damietta	Egypt	Middle East
Nagoya	Japan	Asia	Izmit	Turkey	Europe
Kobe	Japan	Asia	Istanbul Ambarli	Turkey	Europe
Busan	South Korea	Asia	Odessa	Ukraine	Europe
Kwangyang	South Korea	Asia	Ilyichevsk	Ukraine	Europe
Dalian	China	Asia	Constantza	Romania	Europe
Xingang	China	Asia	Piraeus	Greece	Europe
Qingdao	China	Asia	Rijeka	Croatia	Europe
Liangyungang	China	Asia	Koper	Slovenia	Europe
Shanghai	China	Asia	Trieste	Italy	Europe
Ningbo	China	Asia	Gioia Tauro	Italy	Europe
Fuzhou	China	Asia	Genoa	Italy	Europe
Taipei	Taiwan	Asia	Fos	France	Europe
Xiamen	China	Asia	Barcelona	Spain	Europe
Kaohsiung	Taiwan	Asia	Valencia	Spain	Europe
Shenzhen Yantian	China	Asia	Malaga	Spain	Europe
Hong Kong	China	Asia	Algeciras	Spain	Europe
Shenzhen Chiwan	China	Asia	Tangiers	Marocco	Europe
Shenzhen Da Chan Bay	China	Asia	Le Havre	France	Europe
Vung Tau	Vietnam	Asia	Felixstowe	United Kingdom	Europe
Laem Chabang	Thailand	Asia	Zeebrugge	Belgium	Europe
Singapore	Singapore	Asia	Antwerp	Belgium	Europe
Tanjung Pelepas	Malaysia	Asia	Rotterdam	Netherlands	Europe
Port Klang	Malaysia	Asia	Bremerhaven	Germany	Europe
Colombo	Sri Lanka	Asia	Hamburg	Germany	Europe
Jebel Ali	Dubai	Middle East	Gothenburg	Sweden	Europe
Salalah	Oman	Middle East	Aarhus	Denmark	Europe
Jeddah	Saudi Arabia	Middle East	Gdansk	Poland	Europe

Table A.2: Distances between ports

Origin \ Destination	Yokohama	Shimizu	Nagoya	Kobe	Busan	Kwangyang	Dalian	Xingang	Qingdao	Liangyungang	Shanghai	Ningbo	Fuzhou	Taipei	Xiamen	Kaohsiung	Shenzhen Yantian	Hong Kong	Shenzhen Chiwan	Shenzhen Da Chan Bay	Vung Tau	Laem Chabang	Singapore	Tanjung Pelepas	Port Klang	Colombo	Jebel Ali	Salalah	Jeddah
Yokohama	0	96	188	333	626	679	1095	1246	1060	1086	1008	1020	1211	1134	1316	1319	1565	1582	1592	1597	2418	2972	2879	2899	3072	4431	6303	6045	7190
Shimizu	96	0	119	268	560	614	1030	1181	994	1020	942	954	1146	1064	1250	1254	1500	1516	1526	1531	2355	2907	2818	2838	3011	4370	6242	5984	7129
Nagoya	188	119	0	219	511	565	980	1132	945	971	893	905	1097	1028	1201	1205	1451	1467	1477	1482	2322	2858	2771	2791	2964	4323	6195	5937	7082
Kobe	333	268	219	0	341	394	810	961	775	801	729	761	999	917	1103	1107	1353	1369	1379	1384	2213	2760	2679	2699	2872	4231	6103	5845	6990
Busan	626	560	511	341	0	72	503	654	467	493	445	495	752	688	869	898	1120	1137	1147	1152	1977	2551	2483	2503	2676	4035	5907	5649	6794
Kwangyang	679	614	565	394	72	0	437	588	401	427	382	436	699	616	817	840	1062	1084	1094	1099	1905	2493	2428	2448	2621	3980	5852	5594	6739
Dalian	1095	1030	980	810	503	437	0	188	251	324	477	556	843	851	961	1006	1212	1229	1249	1244	2111	2659	2576	2596	2769	4128	6000	5742	6887
Xingang	1246	1181	1132	961	654	588	188	0	394	468	621	699	987	996	1105	1150	1356	1372	1382	1387	2242	2773	2720	2740	2913	4272	6144	5886	7031
Qingdao	1060	994	945	775	467	401	251	394	0	89	307	386	675	697	793	838	1044	1061	1071	1076	1959	2526	2408	2428	2601	3960	5832	5574	6719
Liangyungang	1086	1020	971	801	493	427	324	468	89	0	258	337	626	641	745	790	996	1012	1022	1027	1876	2407	2360	2380	2553	3912	5784	5526	6671
Shanghai	1008	942	893	729	445	382	477	621	307	258	0	101	390	421	509	554	760	776	786	791	1675	2242	2124	2144	2317	3676	5548	5290	6435
Ningbo	1020	954	905	761	495	436	556	699	386	337	101	0	318	355	436	481	687	704	714	719	1572	2103	2051	2071	2244	3603	5475	5217	6362
Fuzhou	1211	1146	1097	999	752	699	843	987	675	626	390	318	0	150	168	235	420	436	456	451	1318	1888	1784	1804	1977	3336	5208	4950	6095
Taipei	1134	1064	1028	917	688	616	851	996	697	641	421	355	150	0	222	224	446	471	481	486	1312	1877	1812	1832	2005	3364	5236	4970	6124
Xiamen	1316	1250	1201	1103	869	817	961	1105	793	745	509	436	168	222	0	166	270	287	297	302	1150	1714	1638	1658	1831	3190	5062	4804	5949
Kaohsiung	1319	1254	1205	1107	898	840	1006	1150	838	790	554	481	235	224	166	0	337	354	364	369	1121	1653	1611	1631	1804	3163	5035	4777	5922
Shenzhen Yantian	1565	1500	1451	1353	1120	1062	1212	1356	1044	996	760	687	420	446	270	337	0	46	56	61	947	1482	1436	1456	1629	2988	4860	4602	5747
Hong Kong	1582	1516	1467	1369	1137	1084	1229	1372	1061	1012	776	704	436	471	287	354	46	0	10	15	927	1489	1410	1430	1603	2962	4834	4576	5721
Shenzhen Chiwan	1592	1526	1477	1379	1147	1094	1249	1382	1071	1022	786	714	456	481	297	364	56	10	0	5	937	1499	1420	1440	1613	2983	4844	4586	5731
Shenzhen Da Chan Bay	1597	1531	1482	1384	1152	1099	1244	1387	1076	1027	791	719	451	486	302	369	61	15	5	0	942	1504	1425	1445	1618	2988	4849	4591	5736
Vung Tau	2418	2355	2322	2213	1977	1905	2111	2242	1959	1876	1675	1572	1318	1312	1150	1121	947	927	937	942	0	681	646	666	839	2198	4070	3796	4958
Laem Chabang	2972	2907	2858	2760	2551	2493	2659	2773	2526	2407	2242	2103	1888	1877	1714	1653	1482	1489	1499	1504	681	0	831	836	1009	2368	4240	3982	5127
Singapore	2879	2818	2771	2679	2483	2428	2576	2720	2408	2360	2124	2051	1784	1812	1638	1611	1436	1410	1420	1425	646	831	0	20	193	1552	3424	3166	4311
Tanjung Pelepas	2899	2838	2791	2699	2503	2448	2596	2740	2428	2380	2144	2071	1804	1832	1658	1631	1456	1430	1440	1445	666	836	20	0	173	1532	3404	3146	4291
Port Klang	3072	3011	2964	2872	2676	2621	2769	2913	2601	2553	2317	2244	1977	2005	1831	1804	1629	1603	1613	1618	839	1009	193	173	0	1370	3243	2985	4130
Colombo	4431	4370	4323	4231	4035	3980	4128	4272	3960	3912	3676	3603	3336	3364	3190	3163	2988	2962	2983	2988	2198	2368	1552	1532	1370	0	1887	1633	2788
Jebel Ali	6303	6242	6195	6103	5907	5852	6000	6144	5832	5784	5548	5475	5208	5236	5062	5035	4860	4834	4844	4849	4070	4240	3424	3404	3243	1887	0	894	2152
Salalah	6045	5984	5937	5845	5649	5594	5742	5886	5574	5526	5290	5217	4950	4970	4804	4777	4602	4576	4586	4591	3796	3982	3166	3146	2985	1633	894	0	1270
Jeddah	7190	7129	7082	6990	6794	6739	6887	7031	6719	6671	6435	6362	6095	6123	5949	5922	5747	5721	5731	5736	4957	5127	4311	4291	4130	2788	2152	1270	0
Port Said	7894	7833	7786	7694	7498	7443	7591	7735	7423	7375	7139	7066	6799	6822	6653	6626	6451	6425	6435	6440	5656	5837	5015	4995	4834	3492	2857	1975	715
Damietta	7925	7864	7817	7725	7519	7426	7622	7766	7454	7406	7170	7097	6830	6842	6674	6657	6482	6456	6466	6471	5668	5806	5036	5025	4854	3508	2888	2006	746
Izmit	8718	8650	8617	8518	8329	8278	8422	8566	8254	8206	7970	7898	7630	7644	7484	7450	7275	7256	7266	7271	6478	6654	5832	5825	5639	4303	3687	2805	1539
Istanbul Ambarli	8669	8608	8561	8469	8273	8219	8366	8510	8198	8150	7914	7841	7574	7591	7428	7401	7226	7200	7210	7215	6425	6599	5790	5770	5609	4267	3632	2750	1490
Odessa	9016	8955	8908	8816	8620	8539	8713	8857	8545	8497	8261	8188	7921	7938	7775	7748	7573	7547	7557	7562	6772	6956	6137	6117	5943	4607	3979	3097	1837
Ilyichevsk	9013	8941	8905	8809	8617	8526	8731	8870	8563	8494	8279	8185	7939	7935	7772	7741	7592	7565	7570	7575	6769	6943	6123	6114	5930	4594	3996	3094	1834
Constantza	8872	8811	8764	8672	8476	8422	8569	8713	8401	8353	8117	8044	7777	7794	7631	7604	7429	7403	7413	7418	6628	6802	5993	5973	5812	4470	3835	2953	1693
Piraeus	8481	8420	8373	8281	8085	8033	8178	8322	8010	7962	7726	7653	7386	7412	7240	7213	7038	7012	7022	7027	6246	6413	5602	5582	5421	4079	3444	2562	1302
Rijeka	9139	9078	9031	8939	8743	8691	8836	8980	8668	8620	8384	8311	8044	8070	7898	7871	7696	7670	7680	7685	6904	7071	6260	6240	6079	4737	4102	3220	1960
Koper	9178	9117	9070	8978	8782	8727	8875	9019	8707	8659	8423	8350	8083	8109	7937	7910	7735	7709	7719	7724	6943	7124	6299	6279	6117	4776	4141	3259	1999
Trieste	9186	9120	9078	8986	8790	8735	8883	9027	8715	8667	8431	8358	8091	8114	7945	7918	7738	7717	7727	7732	6948	7116	6302	6282	6109	4773	4149	3267	2007
Gioia Tauro	8822	8761	8714	8622	8426	8371	8519	8663	8351	8303	8067	7994	7727	7753	7581	7554	7379	7353	7363	7368	6587	6768	5943	5923	5762	4420	3785	2903	1643
Genoa	9305	9244	9197	9105	8909	8854	9002	9146	8834	8786	8550	8477	8210	8237	8064	8037	7862	7836	7847	7852	7071	7252	6426	6406	6245	4903	4268	3386	2126
Fos	9405	9344	9297	9205	9009	8954	9102	9246	8934	8886	8650	8577	8310	8332	8164	8137	7962	7936	7946	7951	7166	7340	6526	6506	6345	5003	4368	3486	2226
Barcelona	9476	9415	9368	9276	9080	9029	9173	9317	9005	8957	8721	8648	8381	8407	8235	8208	8033	8007	8034	8039	7241	7409	6597	6577	6416	5074	4439	3557	2297
Valencia	9556	9495	9448	9356	9160	9109	9253	9397	9085	9037	8801	8728	8461	8487	8315	8288	8113	8087	8097	8102	7321	7489	6677	6657	6496	5154	4519	3637	2377
Malaga	9758	9690	9650	9558	9362	9275	9455	9599	9324	9239	9040	8930	8663	8684	8517	8490	8315	8326	8336	8341	7518	7683	6872	6859	6679	5343	4758	3839	2579
Algeciras	9804	9743	9696	9604	9408	9340	9501	9645	9333	9285	9049	8976	8709	8735	8563	8536	8361	8335	8385	8390	7569	7736	6925	6905	6744	5402	4767	3885	2625
Tangiers	9835	9763	9728	9624	9440	9348	9533	9677	9365	9305	9081	9008	8741	8757	8595	8556	8393	8367	8410	8415	7591	7757	6945	6937	6752	5416	4799	3915	2657
Le Havre	10933	10872	10825	10736	10540	10485	10633	10774	10462	10414	10178	10105	9841	9864	9692	9668	9490	9467	9477	9482	8698	8879	8054	8034	7873	6534	5899	5014	3757
Felixstowe	11056	10995	10948	10856	10663	10605	10756	10897	10585	10537	10301	10228	9961	10013	9815	9788	9613	9587	9640	9645	8847	9014	8177	8157	7996	6657	6019	5137	3877
Zeebrugge	11083	11022	10975	10883	10687	10624	10780	10924	10612	10564	10328	10255	9988	10017	9842	9815	9640	9614	9624	9629	8851	9018	8204	8184	8023	6681	6046	5164	3904
Antwerp	11170	11109	11062	10970	10774	10711	10867	10986	10699	10626	10415	10317	10075	10078	9929	9902	9701	9701	9711	9716	8912	9077	8291	8246	8094	6758	6133	5234	3991
Rotterdam	11133	11072	11025	10933	10737	10688	10830	10974	10662	10614	10378	10305	10038	10081	9892	9865	9690	9664	9674	9679	8915	9082	8254	8234	8084	6742	6107	5214	3965
Bremerhaven	11328	11267	11220	11128	10932	10877	11025	11169	10857	10809	10573	10500	10233	10286	10087	10060	9885	9859	9889	9894	9120	9287	8449	8429	8268	6926	6291	5409	4149
Hamburg	11416	11355	11322	11216	11034	10971	11142	11242	10974	10882	10690	10573	10350	10334	10175	10148	9956	9976	9979	9984	9168	9332	8537	8502	8342	7006	6408	5490	4237
Gothenburg	11568	11507	11460	11368	11175	11117	11268	11409	11097	11049	10813	10740	10476	10524	10327	10300	10125	10099	10141	10146	9358	9525	8689	8669	8508	7169	6531	5649	4389
Aarhus	11662	11601	11554	11462	11269	11127	11419	11391	11248	11025	10964	10721	10615	10454	10421	10394	10276	10250	10258	10263	9453	9620	8783	8763	8602	7263	6682	5626	4483
Gdansk	11792	11731	11684	11592	11386	11293	11489	11633	11321	11273	11037	10964	10697	10833	10541	10524	10349	10323	10509	10514	9726	9893	8903	8892	8721	7375	6755	5873	4613

Origin \ Destination	Port Said	Damietta	Izmit	Istanbul Ambarli	Odessa	Ilyichevsk	Constantza	Piraeus	Rijeka	Koper	Trieste	Gioia Tauro	Genoa	Fos	Barcelona	Valencia	Malaga	Algeciras	Tangiers	Le Havre	Felixstowe	Zeebrugge	Antwerp	Rotterdam	Bremerhaven	Hamburg	Gothenburg	Aarhus	Gdansk
Yokohama	7894	7925	8718	8669	9015	9013	8872	8481	9139	9178	9186	8822	9305	9405	9476	9556	9758	9804	9835	10933	11056	11083	11170	11133	11328	11416	11568	11662	11792
Shimizu	7833	7864	8650	8608	8954	8941	8811	8420	9078	9117	9120	8761	9244	9344	9415	9495	9690	9743	9763	10872	10995	11022	11109	11072	11267	11355	11507	11601	11731
Nagoya	7786	7817	8617	8561	8907	8905	8764	8373	9031	9070	9078	8714	9197	9297	9368	9448	9650	9696	9728	10825	10948	10975	11062	11025	11220	11322	11460	11554	11684
Kobe	7694	7725	8518	8469	8815	8809	8672	8281	8939	8978	8986	8622	9105	9205	9276	9356	9558	9604	9624	10736	10856	10883	10970	10933	11128	11216	11368	11462	11592
Busan	7498	7519	8329	8273	8619	8617	8476	8085	8743	8782	8790	8426	8909	9009	9080	9160	9362	9408	9440	10540	10663	10687	10774	10737	10932	11034	11175	11269	11386
Kwangyang	7443	7426	8278	8219	8539	8526	8422	8033	8691	8727	8735	8371	8854	8954	9029	9109	9275	9340	9348	10485	10605	10624	10711	10690	10877	10971	11117	11127	11293
Dalian	7591	7622	8422	8366	8712	8731	8569	8178	8836	8875	8883	8519	9002	9102	9173	9253	9455	9501	9533	10633	10756	10780	10867	10830	11025	11142	11268	11419	11489
Xingang	7735	7766	8566	8510	8856	8869	8713	8322	8980	9019	9027	8663	9146	9246	9317	9397	9599	9645	9677	10774	10897	10924	10986	10974	11169	11242	11409	11391	11633
Qingdao	7423	7454	8254	8198	8544	8563	8401	8010	8668	8707	8715	8351	8834	8934	9005	9085	9324	9333	9365	10462	10585	10612	10699	10662	10857	10974	11097	11248	11321
Liangyungang	7375	7406	8206	8150	8496	8494	8353	7962	8620	8659	8667	8303	8786	8886	8957	9037	9239	9285	9305	10414	10537	10564	10626	10614	10809	10882	11049	11025	11273
Shanghai	7139	7170	7970	7914	8260	8279	8117	7726	8384	8423	8431	8067	8550	8650	8721	8801	9040	9049	9081	10178	10301	10328	10415	10378	10573	10690	10813	10964	11037
Ningbo	7066	7097	7898	7841	8187	8185	8044	7653	8311	8350	8358	7994	8477	8577	8648	8728	8930	8976	9008	10105	10228	10255	10317	10305	10500	10573	10740	10721	10964
Fuzhou	6799	6830	7630	7574	7920	7939	7777	7386	8044	8083	8091	7727	8210	8310	8381	8461	8663	8709	8741	9841	9961	9988	10075	10038	10233	10350	10476	10615	10697
Taipei	6822	6842	7644	7591	7938	7935	7794	7412	8070	8109	8114	7753	8237	8332	8407	8487	8684	8735	8757	9864	10013	10017	10078	10081	10286	10334	10524	10454	10833
Xiamen	6653	6674	7484	7428	7774	7772	7631	7240	7898	7937	7945	7581	8064	8164	8235	8315	8517	8563	8595	9692	9815	9842	9929	9892	10087	10175	10327	10421	10541
Kaohsiung	6626	6657	7450	7401	7747	7741	7604	7213	7871	7910	7918	7554	8037	8137	8208	8288	8490	8536	8556	9668	9788	9815	9902	9865	10060	10148	10300	10394	10524
Shenzhen Yantian	6451	6482	7275	7226	7572	7592	7429	7038	7696	7735	7738	7379	7862	7962	8033	8113	8315	8361	8393	9490	9613	9640	9701	9690	9885	9956	10125	10276	10349
Hong Kong	6425	6456	7256	7200	7546	7565	7403	7012	7670	7709	7717	7353	7836	7936	8007	8087	8326	8335	8367	9467	9587	9614	9701	9664	9859	9976	10099	10250	10323
Shenzhen Chiwan	6435	6466	7266	7210	7556	7573	7413	7022	7680	7719	7727	7363	7847	7946	8034	8097	8336	8385	8410	9477	9640	9624	9711	9674	9889	9979	10141	10258	10509
Shenzhen Da Chan Bay	6440	6471	7271	7215	7561	7578	7418	7027	7685	7724	7732	7368	7852	7951	8039	8102	8341	8390	8415	9482	9645	9629	9716	9679	9894	9984	10146	10263	10514
Vung Tau	5656	5668	6478	6425	6772	6769	6628	6246	6904	6943	6948	6587	7071	7166	7241	7321	7518	7569	7591	8698	8847	8851	8912	8915	9120	9168	9358	9369	9726
Laem Chabang	5837	5806	6654	6599	6964	6951	6818	6413	7071	7124	7116	6759	7243	7340	7409	7489	7683	7736	7757	8882	9014	9018	9077	9082	9287	9332	9525	9507	9893
Singapore	5015	5036	5832	5790	6136	6123	5993	5602	6260	6299	6302	5943	6426	6526	6597	6677	6872	6925	6945	8054	8177	8204	8291	8254	8449	8537	8689	8783	8903
Tanjung Pelepas	4995	5025	5825	5770	6116	6114	5973	5582	6240	6279	6282	5923	6406	6506	6577	6657	6859	6905	6937	8034	8157	8184	8246	8234	8429	8502	8669	8763	8892
Port Klang	4834	4854	5639	5609	5943	5930	5812	5421	6079	6117	6109	5762	6245	6345	6416	6496	6679	6744	6752	7873	7996	8023	8094	8084	8268	8342	8508	8602	8721
Colombo	3492	3508	4303	4267	4607	4594	4470	4079	4737	4776	4773	4420	4903	5003	5074	5154	5343	5402	5416	6534	6657	6681	6758	6742	6926	7006	7169	7263	7375
Jebel Ali	2857	2888	3687	3632	3979	3996	3835	3444	4102	4141	4149	3785	4268	4368	4439	4519	4758	4767	4799	5899	6019	6046	6133	6107	6291	6408	6531	6682	6755
Salalah	1975	2006	2805	2750	3097	3094	2953	2562	3220	3259	3267	2903	3386	3486	3557	3637	3839	3885	3915	5014	5137	5164	5234	5214	5409	5490	5649	5626	5873
Jeddah	715	746	1539	1490	1837	1834	1693	1302	1960	1999	2007	1643	2126	2226	2297	2377	2579	2625	2657	3757	3877	3904	3991	3965	4149	4237	4389	4483	4613
Port Said	0	31	824	779	1126	1115	982	590	1248	1287	1294	931	1413	1513	1585	1665	1864	1913	1941	3042	3165	3195	3279	3256	3437	3525	3677	3771	3898
Damietta	31	0	848	793	1150	1137	996	607	1265	1307	1310	962	1434	1536	1603	1683	1877	1930	1951	3073	3196	3212	3271	3276	3468	3526	3707	3701	3867
Izmit	824	848	0	55	397	384	251	390	1150	1186	1190	837	1321	1420	1504	1588	1762	1643	1675	2798	3121	3062	3147	3126	3378	3261	3432	3535	3800
Istanbul Ambarli	779	793	55	0	347	344	203	349	1097	1137	1145	790	1273	1373	1460	1542	1731	1698	1730	2853	2976	2992	3079	3053	3248	3336	3487	3582	3829
Odessa	1126	1150	397	347	0	13	170	694	1444	1484	1492	1137	1620	1720	1807	1889	2078	2040	2156	3195	3391	3334	3421	3395	3663	3751	3903	3997	4244
Ilyichevsk	1115	1137	384	344	13	0	160	681	1441	1477	1481	1128	1612	1707	1798	1879	2075	2027	2059	3280	3305	3418	3397	3482	3687	3645	3816	3911	4184
Constantza	982	996	251	203	170	160	0	552	1300	1340	1348	993	1476	1576	1663	1745	1934	1894	2012	3049	3247	3188	3359	3249	3519	3607	3759	3853	4100
Piraeus	590	607	390	349	694	681	552	0	790	829	837	483	966	1066	1153	1235	1432	1484	1505	2614	2737	2773	2847	2834	3009	3095	3249	3343	3590
Rijeka	1248	1265	1150	1097	1444	1441	1300	790	0	103	110	581	1064	1164	1251	1338	1554	1603	1628	2732	2855	2892	2973	2953	3127	3215	3367	3461	3708
Koper	1287	1307	1186	1137	1484	1477	1340	829	103	0	8	620	1103	1202	1290	1377	1593	1642	1667	2772	2894	2931	3009	2992	3166	3254	3406	3500	3747
Trieste	1294	1310	1190	1145	1492	1481	1348	837	110	8	0	625	1109	1208	1296	1383	1598	1647	1672	2777	2925	2936	3014	3000	3205	3260	3436	3531	3804
Gioia Tauro	931	962	837	790	1137	1128	993	483	581	620	625	0	484	583	671	758	973	1022	1047	2152	2275	2311	2389	2372	2547	2635	2787	2881	3128
Genoa	1413	1434	1321	1273	1620	1612	1476	966	1064	1103	1109	484	0	208	350	508	798	847	871	1997	2100	2136	2213	2197	2372	2460	2630	2706	2953
Fos	1513	1536	1420	1373	1720	1707	1576	1066	1164	1202	1208	583	208	0	172	331	641	680	712	1830	1932	1969	2029	2030	2204	2285	2462	2538	2804
Barcelona	1585	1603	1504	1460	1807	1798	1663	1153	1251	1290	1296	671	350	172	0	161	499	513	545	1663	1786	1802	1881	1863	2058	2129	2297	2392	2639
Valencia	1665	1683	1588	1542	1889	1879	1745	1235	1338	1377	1383	758	508	331	161	0	338	382	411	1512	1635	1672	1752	1712	1907	1995	2147	2241	2488
Malaga	1864	1877	1762	1731	2078	2075	1934	1432	1554	1593	1598	973	798	641	499	338	0	65	87	1219	1343	1358	1429	1422	1627	1677	1854	1949	2222
Algeciras	1913	1930	1643	1698	2064	2054	1894	1484	1603	1642	1647	1022	847	680	513	382	65	0	32	1155	1278	1294	1370	1355	1550	1618	1789	1884	2131
Tangiers	1941	1951	1675	1730	2077	2059	1933	1505	1628	1667	1672	1047	871	712	545	411	87	32	0	1137	1273	1276	1347	1340	1545	1595	1786	1869	2154
Le Havre	3042	3073	2798	2853	3195	3280	3049	2614	2732	2772	2777	2152	1997	1830	1663	1512	1219	1155	1137	0	163	171	252	232	431	500	674	769	1015
Felixstowe	3165	3196	3121	2976	3323	3332	3179	2737	2855	2894	2925	2275	2100	1932	1786	1635	1343	1278	1273	163	0	83	141	123	303	360	530	606	872
Zeebrugge	3195	3212	3062	2992	3334	3336	3188	2773	2892	2931	2936	2311	2136	1969	1802	1672	1358	1294	1276	171	83	0	87	64	269	347	519	627	861
Antwerp	3279	3271	3147	3079	3421	3397	3280	2847	2973	3009	3014	2389	2213	2029	1881	1752	1429	1370	1347	252	141	87	0	149	356	405	597	680	965
Rotterdam	3256	3276	3126	3053	3395	3400	3249	2834	2953	2992	3000	2372	2197	2030	1863	1712	1422	1355	1340	232	123	64	149	0	215	305	467	584	809
Bremerhaven	3437	3468	3331	3248	3595	3605	3451	3009	3127	3166	3205	2547	2372	2204	2058	1907	1627	1550	1545	431	303	269	356	215	0	117	344	456	686
Hamburg	3525	3526	3261	3336	3683	3645	3539	3095	3215	3254	3260	2635	2460	2285	2129	1995	1677	1618	1595	500	360	347	405	305	117	0	402	485	770
Gothenburg	3677	3707	3432	3487	3834	3843	3690	3249	3367	3406	3436	2787	2630	2462	2297	2147	1854	1789	1786	674	530	519	597	467	344	402	0	151	368
Aarhus	3771	3701	3527	3582	3929	3938	3785	3343	3461	3500	3531	2881	2706	2538	2392	2241	1949	1884	1869	769	606	627	680	584	456	485	151	0	379
Gdansk	3898	3867	3800	3829	4176	4211	4032	3590	3708	3747	3804	3128	2953	2804	2639	2488	2222	2131	2154	1015	872	861	965	809	686	770	368	379	0

Table A.3: Demand between ports

Origin \ Destination	Yokohama	Shimizu	Nagoya	Kobe	Busan	Kwangyang	Dalian	Xingang	Qingdao	Liangyungang	Shanghai	Ningbo	Fuzhou	Taipei	Xiamen	Kaohsiung	Shenzhen Yantian	Hong Kong	Shenzhen Chiwan	Shenzhen Da Chan Bay	Vung Tau	Laem Chabang	Singapore	Tanjung Pelepas	Port Klang	Colombo	Jebel Ali	Salalah	Jeddah
Yokohama	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9826	3083	2731
Shimizu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1756	551	488
Nagoya	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7419	2328	2062
Kobe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7891	2476	2193
Busan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41983	13171	11667
Kwangyang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6358	1995	1767
Dalian	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15986	5015	4442
Xingang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30552	9585	8490
Qingdao	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36031	11304	10013
Liangyungang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10608	3328	2948
Shanghai	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87801	27546	24399
Ningbo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36884	11572	10250
Fuzhou	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4132	1296	1148
Taipei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3512	1102	976
Xiamen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16436	5157	4568
Kaohsiung	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30136	9455	8374
Shenzhen Yantian	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42727	13405	11874
Hong Kong	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	73688	23118	20477
Shenzhen Chiwan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16023	5027	4453
Shenzhen Da Chan Bay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5341	1676	1484
Vung Tau	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6496	2038	1805
Laem Chabang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16230	5092	4510
Singapore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90837	28499	25243
Tanjung Pelepas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21071	6611	5855
Port Klang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25670	8054	7134
Colombo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12166	3817	3381
Jebel Ali	3215	575	2428	2582	13737	2080	5231	9997	11790	3471	28730	12069	1352	1149	5378	9861	13981	24112	5243	1748	2126	5311	29723	6895	8400	3981	0	0	0
Salalah	1009	180	762	810	4310	653	1641	3136	3699	1089	9014	3786	424	361	1687	3094	4386	7565	1645	548	667	1666	9325	2163	2635	1249	0	0	0
Jeddah	893	160	675	718	3818	578	1454	2778	3276	965	7984	3354	376	319	1495	2740	3885	6700	1457	486	591	1476	8260	1916	2334	1106	0	0	0
Port Said	1003	179	757	805	4285	649	1632	3118	3678	1083	8962	3765	422	358	1678	3076	4361	7521	1635	545	663	1657	9272	2151	2620	1242	0	0	0
Damietta	321	57	242	257	1370	207	522	997	1176	346	2865	1203	135	115	536	983	1394	2404	523	174	212	530	2964	687	838	397	0	0	0
Izmit	53	9	40	42	226	34	86	164	194	57	472	198	22	19	88	162	230	396	86	29	35	87	489	113	138	65	210	66	58
Istanbul Ambarli	621	111	469	499	2653	402	1010	1931	2277	670	5549	2331	261	222	1039	1904	2700	4657	1013	338	411	1026	5741	1332	1622	769	2469	775	686
Odessa	42	7	31	33	178	27	68	130	153	45	373	156	18	15	70	128	181	313	68	23	28	69	385	89	109	52	166	52	46
Ilyichevsk	32	6	24	26	137	21	52	100	118	35	287	121	14	11	54	99	140	241	52	17	21	53	297	69	84	40	128	40	36
Constantza	201	36	152	161	859	130	327	625	737	217	1796	754	85	72	336	616	874	1507	328	109	133	332	1858	431	525	249	799	251	222
Piraeus	475	85	358	381	2028	307	772	1476	1741	512	4241	1782	200	170	794	1456	2064	3560	774	258	314	784	4388	1018	1240	588	1887	592	524
Rijeka	49	9	37	39	210	32	80	153	180	53	438	184	21	18	82	150	213	368	80	27	32	81	453	105	128	61	195	61	54
Koper	116	21	88	93	496	75	189	361	426	125	1037	436	49	41	194	356	505	870	189	63	77	192	1073	249	303	144	461	145	128
Trieste	94	17	71	75	400	61	152	291	344	101	837	352	39	33	157	287	407	703	153	51	62	155	866	201	245	116	372	117	103
Gioia Tauro	947	169	715	761	4046	613	1541	2945	3473	1022	8462	3555	398	338	1584	2904	4118	7102	1544	515	626	1564	8755	2031	2474	1173	3765	1181	1046
Genoa	519	93	392	417	2216	336	844	1613	1902	560	4635	1947	218	185	868	1591	2256	3890	846	282	343	857	4795	1112	1355	642	2062	647	573
Fos	299	53	225	240	1275	193	486	928	1095	322	2667	1121	126	107	499	916	1298	2239	487	162	197	493	2760	640	780	370	1187	372	330
Barcelona	609	109	460	489	2601	394	991	1893	2233	657	5441	2285	256	218	1018	1867	2648	4566	993	331	403	1006	5629	1306	1591	754	2421	759	673
Valencia	1236	221	933	992	5280	800	2011	3843	4532	1334	11043	4639	520	442	2067	3790	5374	9268	2015	672	817	2041	11425	2650	3229	1530	4913	1541	1365
Malaga	98	18	74	79	419	63	160	305	360	106	876	368	41	35	164	301	426	735	160	53	65	162	906	210	256	121	390	122	108
Algeciras	1029	184	777	826	4397	666	1674	3200	3774	1111	9196	3863	433	368	1721	3156	4475	7718	1678	559	680	1700	9514	2207	2689	1274	4092	1284	1137
Tangiers	338	60	255	272	1445	219	550	1052	1240	365	3022	1270	142	121	566	1037	1471	2536	552	184	224	559	3127	725	884	419	1345	422	374
Le Havre	744	133	562	598	3179	481	1211	2314	2728	803	6649	2793	313	266	1245	2282	3236	5580	1213	404	492	1229	6879	1596	1944	921	2958	928	822
Felixstowe	1048	187	792	842	4480	678	1706	3260	3845	1132	9369	3936	441	375	1754	3216	4559	7863	1710	570	693	1732	9693	2248	2739	1298	4168	1308	1158
Zeebrugge	787	141	595	632	3364	510	1281	2448	2887	850	7036	2956	331	281	1317	2415	3424	5905	1284	428	521	1301	7280	1689	2057	975	3131	982	870
Antwerp	2472	442	1867	1985	10563	1600	4022	7687	9066	2669	22091	9280	1040	884	4135	7582	10750	18540	4031	1344	1634	4084	22855	5302	6459	3061	9829	3084	2731
Rotterdam	3295	589	2488	2646	14080	2132	5361	10247	12084	3558	29446	12370	1386	1178	5512	10107	14330	24713	5374	1791	2179	5443	30465	7067	8609	4080	13102	4110	3641
Bremerhaven	1534	274	1158	1232	6555	993	2496	4770	5625	1656	13708	5759	645	548	2566	4705	6671	11505	2502	834	1014	2534	14182	3290	4008	1899	6099	1914	1695
Hamburg	2371	424	1790	1904	10130	1534	3857	7372	8694	2560	21186	8900	997	847	3966	7271	10310	17780	3866	1289	1567	3916	21918	5084	6194	2936	9426	2957	2619
Gothenburg	277	49	209	222	1182	179	450	860	1014	299	2471	1038	116	99	463	848	1202	2074	451	150	183	457	2556	593	722	342	1099	345	306
Aarhus	231	41	174	186	987	149	376	718	847	249	2064	867	97	83	386	708	1005	1732	377	126	153	382	2136	495	604	286	918	288	255
Gdansk	81	15	61	65	348	53	132	253	298	88	727	305	34	29	136	250	354	610	133	44	54	134	752	175	213	101	324	102	90

Origin \ Destination	Port Said	Damietta	Izmit	Istanbul Ambarli	Odessa	Ilyichevsk	Constantza	Piraeus	Rijeka	Koper	Trieste	Gioia Tauro	Genoa	Fos	Barcelona	Valencia	Malaga	Algeciras	Tangiers	Le Havre	Felixstowe	Zeebrugge	Antwerp	Rotterdam	Bremerhaven	Hamburg	Gothenburg	Aarhus	Gdansk
Yokohama	3065	980	138	1622	109	84	525	1240	128	303	245	2473	1355	780	1590	3228	256	2688	883	1943	2738	2057	6457	8606	4007	6192	722	603	213
Shimizu	548	175	25	290	19	15	94	222	23	54	44	442	242	139	284	577	46	480	158	347	489	368	1154	1538	716	1107	129	108	38
Nagoya	2314	740	104	1225	82	63	396	936	97	229	185	1868	1023	589	1201	2437	193	2029	667	1467	2068	1553	4875	6499	3025	4676	545	456	160
Kobe	2462	787	111	1302	87	67	422	996	103	243	196	1986	1088	626	1277	2592	206	2158	709	1561	2199	1652	5185	6912	3218	4973	580	484	171
Busan	13096	4186	590	6929	465	359	2243	5297	547	1295	1045	10567	5788	3331	6794	13790	1094	11484	3774	8303	11700	8787	27587	36772	17118	26456	3086	2578	908
Kwangyang	1983	634	89	1049	70	54	340	802	83	196	158	1600	877	504	1029	2088	166	1739	572	1257	1772	1331	4178	5569	2592	4006	467	390	138
Dalian	4986	1594	225	2638	177	137	854	2017	208	493	398	4024	2204	1268	2587	5251	417	4373	1437	3161	4455	3346	10504	14001	6518	10074	1175	981	346
Xingang	9530	3047	429	5043	339	261	1632	3854	398	943	761	7690	4212	2424	4944	10035	796	8357	2747	6042	8514	6394	20076	26760	12458	19253	2246	1876	661
Qingdao	11239	3593	506	5947	399	308	1925	4546	470	1112	897	9069	4967	2859	5831	11835	939	9855	3239	7126	10041	7541	23676	31558	14692	22705	2648	2212	779
Liangyungang	3309	1058	149	1751	118	91	567	1338	138	327	264	2670	1463	842	1717	3485	276	2902	954	2098	2956	2220	6971	9292	4326	6685	780	651	229
Shanghai	27388	8755	1234	14491	973	751	4691	11077	1144	2709	2186	22100	12105	6966	14209	28840	2288	24016	7893	17364	24468	18376	57694	76903	35801	55329	6453	5391	1899
Ningbo	11505	3678	518	6087	409	315	1970	4653	481	1138	918	9284	5085	2926	5969	12115	961	10089	3316	7294	10279	7719	24236	32305	15039	23243	2711	2265	798
Fuzhou	1289	412	58	682	46	35	221	521	54	127	103	1040	570	328	669	1357	108	1130	371	817	1151	865	2715	3619	1685	2604	304	254	89
Taipei	1095	350	49	580	39	30	188	443	46	108	87	884	484	279	568	1154	92	961	316	695	979	735	2308	3076	1432	2213	258	216	76
Xiamen	5127	1639	231	2713	182	141	878	2074	214	507	409	4137	2266	1304	2660	5399	428	4496	1478	3251	4580	3440	10800	14396	6702	10358	1208	1009	356
Kaohsiung	9400	3005	423	4974	334	258	1610	3802	393	930	750	7585	4155	2391	4877	9899	785	8243	2709	5960	8398	6307	19802	26395	12288	18990	2215	1850	652
Shenzhen Yantian	13328	4260	600	7052	473	365	2283	5390	557	1318	1064	10755	5891	3390	6914	14034	1113	11687	3841	8450	11907	8942	28076	37423	17422	26925	3140	2623	924
Hong Kong	22986	7348	1035	12162	816	630	3937	9296	961	2273	1835	18548	10159	5846	11925	24204	1920	20156	6624	14573	20535	15422	48420	64541	30046	46435	5416	4524	1594
Shenzhen Chiwan	4998	1598	225	2644	178	137	856	2021	209	494	399	4033	2209	1271	2593	5263	418	4383	1440	3169	4465	3353	10528	14034	6533	10097	1178	984	347
Shenzhen Da Chan Bay	1666	533	75	881	59	46	285	674	70	165	133	1344	736	424	864	1754	139	1461	480	1056	1488	1118	3509	4678	2178	3366	393	328	116
Vung Tau	2026	648	91	1072	72	56	347	820	85	200	162	1635	896	515	1051	2134	169	1777	584	1285	1810	1360	4268	5690	2649	4093	477	399	141
Laem Chabang	5063	1618	228	2679	180	139	867	2048	212	501	404	4085	2238	1288	2627	5331	423	4439	1459	3210	4523	3397	10665	14216	6618	10228	1193	997	351
Singapore	28335	9058	1276	14992	1007	777	4853	11460	1184	2802	2262	22864	12523	7207	14700	29837	2367	24847	8166	17965	25314	19012	59689	79562	37039	57242	6676	5577	1965
Tanjung Pelepas	6573	2101	296	3478	233	180	1126	2658	275	650	525	5304	2905	1672	3410	6921	549	5763	1894	4167	5872	4410	13846	18455	8592	13278	1549	1294	456
Port Klang	8007	2560	361	4237	284	220	1371	3239	335	792	639	6461	3539	2037	4154	8432	669	7022	2308	5077	7154	5373	16868	22484	10467	16177	1887	1576	555
Colombo	3795	1213	171	2008	135	104	650	1535	159	375	303	3062	1677	965	1969	3996	317	3328	1094	2406	3390	2546	7994	10656	4961	7667	894	747	263
Jebel Ali	0	0	180	2110	142	109	683	1613	167	394	318	3217	1762	1014	2069	4199	333	3496	1149	2528	3562	2675	8400	11196	5212	8055	940	785	277
Salalah	0	0	56	662	44	34	214	506	52	124	100	1009	553	318	649	1317	105	1097	361	793	1118	839	2635	3513	1635	2527	295	246	87
Jeddah	0	0	50	586	39	30	190	448	46	110	88	894	490	282	575	1167	93	972	319	703	990	743	2334	3111	1448	2239	261	218	77
Port Said	0	0	56	658	44	34	213	503	52	123	99	1004	550	316	645	1310	104	1091	358	789	1111	835	2620	3492	1626	2513	293	245	86
Damietta	0	0	18	210	14	11	68	161	17	39	32	321	176	101	206	419	33	349	115	252	355	267	838	1116	520	803	94	78	28
Izmit	66	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Istanbul Ambarli	770	246	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Odessa	52	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ilyichevsk	40	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Constantza	249	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Piraeus	589	188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rijeka	61	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Koper	144	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trieste	116	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gioia Tauro	1174	375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Genoa	643	206	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fos	370	118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barcelona	755	241	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Valencia	1533	490	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Malaga	122	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Algeciras	1276	408	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tangiers	419	134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Le Havre	923	295	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Felixstowe	1300	416	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zeebrugge	977	312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Antwerp	3066	980	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rotterdam	4087	1306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremerhaven	1903	608	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	2940	940	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gothenburg	343	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aarhus	286	92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gdansk	101	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.4: Liner ship characteristics

Ship Name	Ship Capacity (TEU)	Frequency (per week)	Total Capacity (TEU/year)	Capital Cost ($/year)	Operating Cost ($/year)
M1	4000	1	208000	4500000	3600000
M2	5000	1	260000	5400000	4050000
M3	6000	1	312000	6000000	4350000
M4	7000	1	364000	6500000	4600000
M5	8000	1	416000	7000000	4850000
M6	4000	2	416000	9000000	5850000
M7	9000	1	468000	7500000	5100000
M8	10000	1	520000	8000000	5350000
M9	5000	2	520000	10800000	6750000
M10	11000	1	572000	8500000	5600000
M11	12000	1	624000	9000000	5850000
M12	6000	2	624000	12000000	7350000
M13	4000	3	624000	13500000	8100000
M14	13000	1	676000	9500000	6100000
M15	14000	1	728000	10000000	7850000
M16	7000	2	728000	13000000	6350000
M17	5000	3	780000	16200000	9450000

Table A.5: Feeder ship characteristics

Ship Name	Ship Capacity (TEU)	Total Capacity (TEU/year)	Capital Cost ($/year)	Operating Cost ($/year)	Fuel cost ($/nm)
F1	200	10400	800000	1450000	16.667
F2	350	18200	950000	1525000	20.833
F3	500	26000	1100000	1600000	25.000
F4	700	36400	1400000	1750000	26.667
F5	800	41600	1500000	1800000	29.167
F6	900	46800	1600000	1850000	31.667
F7	1000	52000	1750000	1925000	33.333
F8	1250	65000	2100000	2100000	41.667
F9	1500	78000	2300000	2200000	50.000
F10	1750	91000	2500000	2300000	58.333
F11	2000	104000	2700000	2400000	66.667
F12	2250	117000	2950000	2525000	75.000
F13	2500	130000	3200000	2650000	83.333
F14	4000	208000	4500000	3600000	91.626
F15	5000	260000	5400000	4050000	104.264
F16	6000	312000	6000000	4350000	116.902
F17	7000	364000	6500000	4600000	129.540
F18	8000	416000	7000000	4850000	142.178
F19	9000	468000	7500000	5100000	154.816
F20	10000	520000	8000000	5350000	167.454

Table A.6: Fuel cost for different speeds and ship sizes

Ship	Speed																
Name	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	23.5	24	24.5	25	25.5	26
M1	85.637	84.925	84.250	83.610	83.002	83.870	84.696	88.242	91.626	94.860	101.820	108.483	114.869	120.995	126.875	132.525	137.957
M2	97.449	96.639	95.871	95.143	94.451	95.438	96.379	100.413	104.264	107.944	115.864	123.447	130.713	137.684	144.375	150.804	156.986
M3	109.261	108.353	107.492	106.675	105.900	107.006	108.061	112.584	116.902	121.028	129.908	138.410	146.557	154.372	161.875	169.083	176.014
M4	121.073	120.067	119.113	118.208	117.348	118.575	119.743	124.755	129.540	134.112	143.952	153.373	162.401	171.061	179.375	187.363	195.043
M5	132.886	131.780	130.734	129.740	128.797	130.143	131.425	136.927	142.178	147.196	157.996	168.336	178.245	187.750	196.875	205.642	214.071
M6	171.275	169.850	168.501	167.221	166.005	167.740	169.393	176.483	183.252	189.720	203.639	216.967	229.739	241.989	253.750	265.049	275.914
M7	144.698	143.494	142.354	141.273	140.245	141.711	143.107	149.098	154.816	160.280	172.040	183.299	194.090	204.439	214.375	223.921	233.100
M8	156.510	155.208	153.975	152.805	151.694	153.280	154.790	161.269	167.454	173.364	186.084	198.263	209.934	221.128	231.875	242.200	252.129
M9	194.899	193.278	191.742	190.286	188.902	190.876	192.757	200.826	208.528	215.888	231.727	246.893	261.427	275.367	288.750	301.608	313.972
M10	168.322	166.922	165.596	164.338	163.143	164.848	166.472	173.441	180.092	186.449	200.128	213.226	225.778	237.817	249.375	260.480	271.157
M11	180.134	178.636	177.217	175.870	174.591	176.416	178.154	185.612	192.730	199.533	214.172	228.189	241.622	254.506	266.875	278.759	290.186
M12	218.523	216.706	214.984	213.351	211.799	214.013	216.121	225.168	233.804	242.056	259.816	276.819	293.115	308.745	323.750	338.167	352.029
M13	256.912	254.776	252.751	250.831	249.007	251.610	254.089	264.725	274.878	284.579	305.459	325.450	344.608	362.984	380.625	397.574	413.872
M14	191.946	190.350	188.837	187.403	186.040	187.984	189.836	197.783	205.369	212.617	228.216	243.152	257.466	271.195	284.375	297.038	309.214
M15	203.758	202.063	200.458	198.935	197.488	199.553	201.519	209.954	218.007	225.701	242.261	258.115	273.310	287.884	301.875	315.317	328.243
M16	242.147	240.133	238.226	236.416	234.696	237.150	239.486	249.511	259.080	268.224	287.904	306.746	324.803	342.123	358.750	374.725	390.086
M17	292.348	289.917	287.614	285.429	283.353	286.315	289.136	301.239	312.792	323.832	347.591	370.340	392.140	413.051	433.125	452.412	470.957

Appendix B

Maersk route network

Table B.1: Routes in the Maersk network

AE1/AE10	AE10/AE1	AE2	AE3	AE6
Yokohama	Shenzhen Yantian	Busan	Dalian	Yokohama
Hong Kong	Hong Kong	Xingang	Xingang	Nagoya
Shenzhen Yantian	Tanjung Pelepas	Dalian	Busan	Shanghai
Tanjung Pelepas	Le Havre	Qingdao	Shanghai	Ningbo
Felixstowe	Zeebrugge	Kwangyang	Ningbo	Xiamen
Rotterdam	Hamburg	Shanghai	Taipei	Hong Kong
Hamburg	Gdansk	Bremerhaven	Shenzhen Chiwan	Shenzhen Yantian
Bremerhaven	Gothenburg	Hamburg	Shenzhen Yantian	Tanjung Pelepas
Tangiers	Aarhus	Rotterdam	Tanjung Pelepas	Jeddah
Jeddah	Bremerhaven	Felixstowe	Port Klang	Barcelona
Jebel Ali	Rotterdam	Antwerp	Port Said	Valencia
Shenzhen Da Chan Bay	Singapore	Tanjung Pelepas	Damietta	Algeciras
Ningbo	Hong Kong	Busan	Izmit	Tangiers
Shanghai	Kobe		Istanbul Ambarli	Tanjung Pelepas
Kaohsiung	Nagoya		Constantza	Vung Tau
Yokohama	Shimizu		Ilyichevsk	Shenzhen Yantian
	Yokohama		Odessa	Hong Kong
	Shenzhen Yantian		Damietta	Yokohama
			Port Said	
			Port Klang	
			Tanjung Pelepas	
			Dalian	

AE7	AE9	AE11	AE12
Shanghai	Laem Chabang	Qingdao	Shanghai
Ningbo	Tanjung Pelepas	Shanghai	Busan
Xiamen	Port Klang	Fuzhou	Hong Kong
Hong Kong	Colombo	Hong Kong	Shenzhen Chiwan
Shenzhen Yantian	Zeebrugge	Shenzhen Chiwan	Tanjung Pelepas
Algeciras	Felixstowe	Shenzhen Yantian	Port Klang
Tangiers	Bremerhaven	Tanjung Pelepas	Port Said
Rotterdam	Rotterdam	Port Klang	Piraeus
Felixstowe	Le Havre	Salalah	Koper
Bremerhaven	Tangiers	Port Said	Rijeka
Malaga	Salalah	Gioia Tauro	Trieste
Shenzhen Yantian	Colombo	Genoa	Damietta
Hong Kong	Port Klang	Fos	Port Said
Shanghai	Singapore	Genoa	Jeddah
	Laem Chabang	Damietta	Port Klang
		Port Said	Singapore
		Salalah	Shanghai
		Port Klang	
		Singapore	
		Liangyungang	
		Qingdao	

Table B.2: Ships and capacities on the Maersk network

AE1/AE10	Capacity	AE10/AE1	Capacity	AE2	Capacity
Sofie Maersk	8160	A.P. Moller	8160	Maersk Seville	8478
Albert Maersk	8272	Skagen Maersk	8160	Maersk Saigon	8450
Carsten Maersk	8160	Sally Maersk	8160	Adrian Maersk	8272
Maersk Singapore	8478	Arnold Maersk	8272	Maersk Salina	8600
Clementine Maersk	8648	Svendborg Maersk	8160	Maersk Savannah	8600
Maersk Seoul	8450	Svend Maersk	8160	Anna Maersk	8272
Maersk Taurus	8400	Columbine Maersk	8648	Arthur Maersk	8272
Sine Maersk	8160	Maersk Tukang	8400	Maersk Stepnica	8600
Axel Maersk	8272	Clifford Maersk	8160	Maersk Semarang	8400
Cornelia Maersk	8650	Maersk Salalah	8600	Maersk Stralsund	8450
		Maersk Stockholm	8600		
Average	8365		8316		8439

AE3		AE6		AE7	
Maersk Kinloss	6500	Mathilde Maersk	9038	Eugen Maersk	14770
CMA CGM Debussy	6627	Maersk Antares	9200	Elly Maersk	14770
Maersk Kuantan	6500	Gunvor Maersk	9074	Evelyn Maersk	14770
Maersk Kowloon	6500	Mette Maersk	9038	Edith Maersk	14770
CMA CGM Corneille	6500	Marit Maersk	9038	Estelle Maersk	14770
Maersk Kelso	6500	Gerd Maersk	9074	Maersk Algol	9200
CMA CGM Musset	6540	Maersk Altair	9200	Ebba Maersk	14770
Maersk Kwangyang	6500	Gudrun Maersk	9074	Eleonora Maersk	14770
CMA CGM Bizet	6627	Marchen Maersk	9038	Emma Maersk	14770
Maersk Kensington	6500	Maren Maersk	9038	Gjertrud Maersk	9074
CMA CGM Baudelaire	6251	Georg Maersk	9074		
		Grete Maersk	9074		
		Maersk Alfirk	9200		
		Margrethe Maersk	9038		
Average	6504		9086		13643

AE9		AE11		AE12	
Maersk Sembawang	6478	Charlotte Maersk	8194	Maersk Kyrenia	6978
Maersk Sebarok	6478	Maersk Surabaya	8400	Safmarine Komati	6500
Maersk Serangoon	6478	Maersk Santana	8478	CMA CGM Belioz	6627
SL New York	6420	CMA CGM Faust	8204	Safmarine Kariba	6500
Maersk Seletar	6478	Soroe Maersk	8160	CMA CGM Balzac	6251
Maersk Kendal	6500	Susan Maersk	8160	Maersk Karachi	6930
Maersk Sentosa	6478	Caroline Maersk	8160	CMA CGM Ravel	6712
Maers Semakau	6478	Cornelius Maersk	8160	CMA CGM Flaubert	6638
Maersk Senang	6478	Chastine Maersk	8160	CMA CGM Voltaire	6456
Average	6474		8230		6621

Appendix C

Cluster design

Table C.1: Cluster design in case of ten clusters

Shanghai	Hong Kong	Singapore	Colombo	Jebel Ali
Yokohama	Xiamen	Vung Tau	Colombo	Jebel Ali
Shimizu	Kaohsiung	Laem Chabang		Salalah
Nagoya	Shenzhen Yantian	Singapore		
Kobe	Hong Kong	Tanjung Pelepas		
Busan	Shenzhen Chiwan	Port Klang		
Kwangyang	Shenzhen Da Chan Bay			
Dalian				
Xingang				
Qingdao				
Liangyungang				
Shanghai				
Ningbo				
Fuzhou				
Taipei				

Port Said	Valencia	Rotterdam	Antwerp	Hamburg
Izmit	Gioia Tauro	Zeebrugge	Antwerp	Bremerhaven
Odessa	Genoa	Le Havre		Hamburg
Jeddah	Fos	Felixstowe		Gothenburg
Port Said	Barcelona	Rotterdam		Aarhus
Damietta	Valencia			Gdansk
Istanbul Ambarli	Malaga			
Ilyichevsk	Algeciras			
Constantza	Tangiers			
Piraeus				
Rijeka				
Koper				
Trieste				

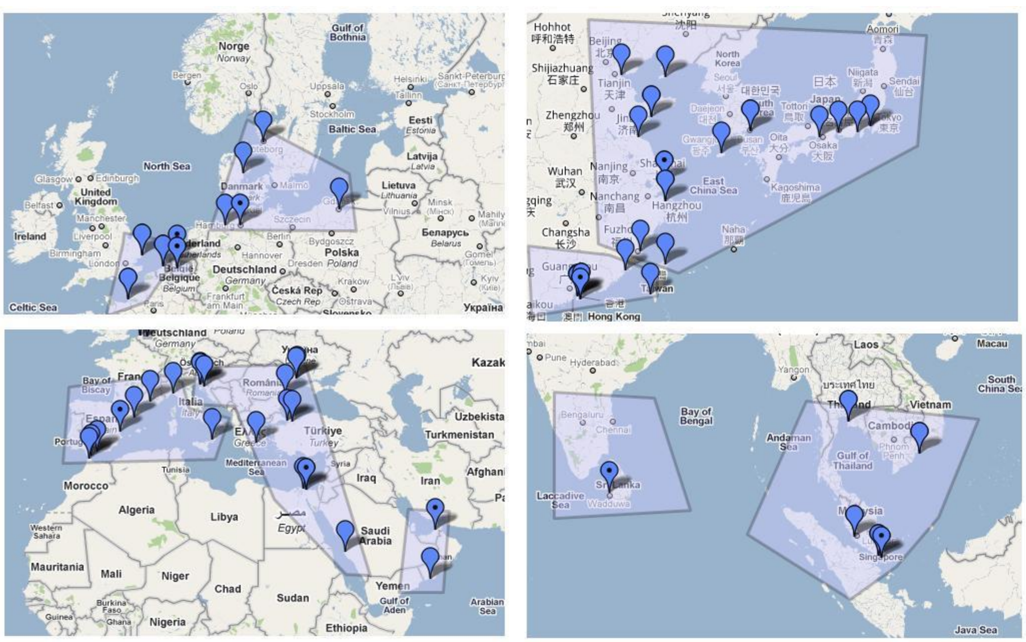

Figure C.1: Graphical representation of the cluster design in case of ten clusters (© Google Maps)

Table C.2: Cluster design in case of twelve clusters

Busan	Shanghai	Shenzhen Yantian	Hong Kong	Singapore	Colombo
Yokohama	Dalian	Xiamen	Hong Kong	Vung Tau	Colombo
Shimizu	Xingang	Kaohsiung	Shenzhen Chiwan	Laem Chabang	
Nagoya	Qingdao	Shenzhen Yantian	Shenzhen Da Chan Bay	Singapore	
Kobe	Liangyungang			Tanjung Pelepas	
Busan	Shanghai			Port Klang	
Kwangyang	Ningbo				
	Fuzhou				
	Taipei				

Jebel Ali	Port Said	Valencia	Rotterdam	Antwerp	Hamburg
Jebel Ali	Izmit	Gioia Tauro	Zeebrugge	Antwerp	Bremerhaven
Salalah	Odessa	Genoa	Le Havre		Hamburg
	Jeddah	Fos	Felixstowe		Gothenburg
	Port Said	Barcelona	Rotterdam		Aarhus
	Damietta	Valencia			Gdansk
	Istanbul Ambarli	Malaga			
	Ilyichevsk	Algeciras			
	Constantza	Tangiers			
	Piraeus				
	Rijeka				
	Koper				
	Trieste				

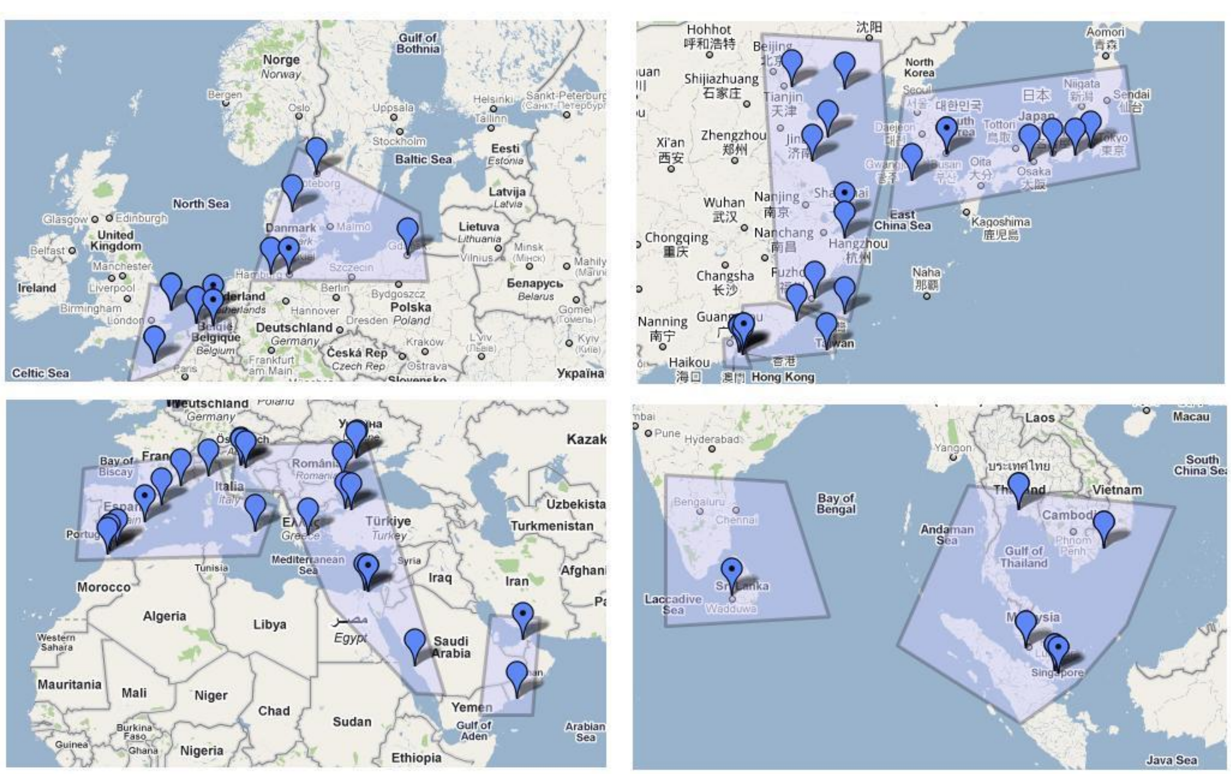

Figure C.2: Graphical representation of the cluster design in case of twelve clusters (© Google Maps)

Table C.3: Cluster design in case of fifteen clusters

Busan	Qingdao	Shanghai	Ningbo	Shenzhen Yantian	Hong Kong	Singapore	Colombo
Yokohama	Dalian	Shanghai	Ningbo	Xiamen	Hong Kong	Vung Tau	Colombo
Shimizu	Xingang		Fuzhou	Kaohsiung	Shenzhen Chiwan	Laem Chabang	
Nagoya	Qingdao		Taipei	Shenzhen Yantian	Shenzhen DCB	Singapore	
Kobe	Liangyungang					Tanjung Pelepas	
Busan						Port Klang	
Kwangyang							

Jebel Ali	Port Said	Valencia	Rotterdam	Antwerp	Hamburg	Bremerhaven
Jebel Ali	Izmit	Gioia Tauro	Zeebrugge	Antwerp	Hamburg	Bremerhaven
Salalah	Odessa	Genoa	Le Havre			Gothenburg
	Jeddah	Fos	Felixstowe			Aarhus
	Port Said	Barcelona	Rotterdam			Gdansk
	Damietta	Valencia				
	Istanbul Ambarli	Malaga				
	Ilyichevsk	Algeciras				
	Constantza	Tangiers				
	Piraeus					
	Rijeka					
	Koper					
	Trieste					

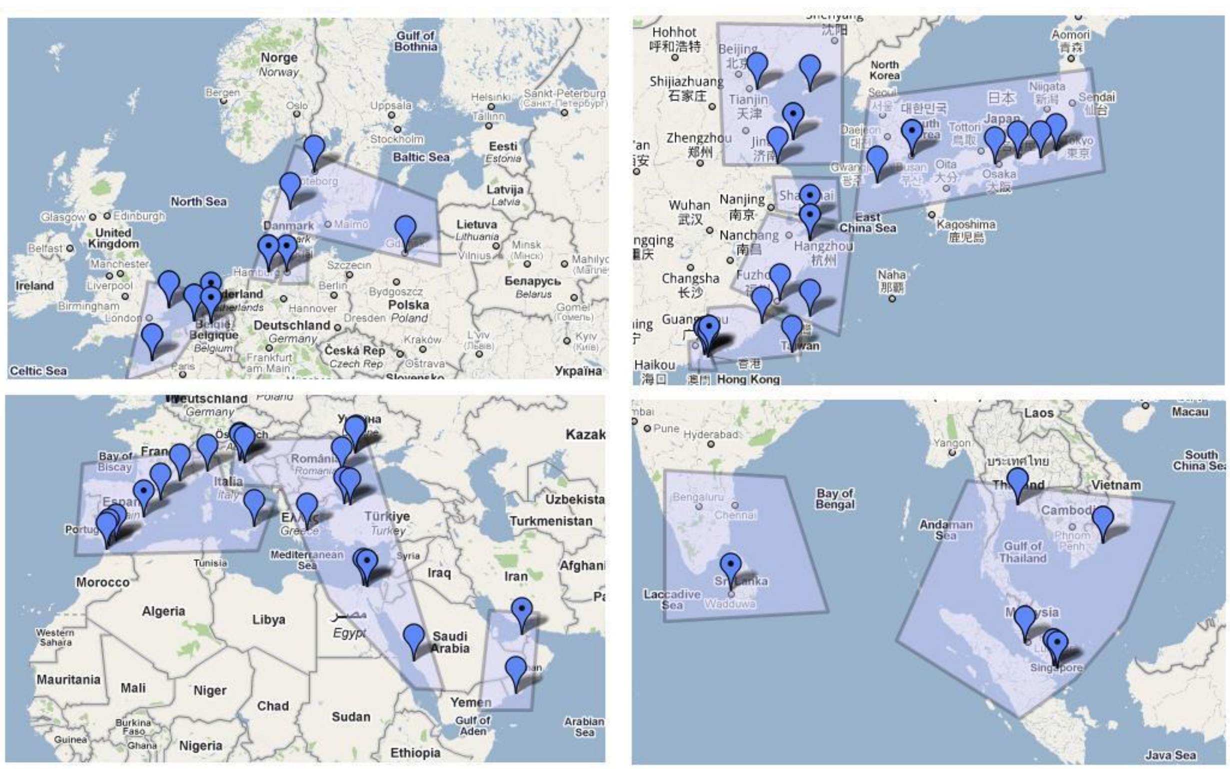

Figure C.3: Graphical representation of the cluster design in case of fifteen clusters (© Google Maps)

Appendix D

Results comparison cargo allocation model with heuristics

Table D.1: Results of the basic case

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.541	-0.522	0.885	1.173
Revenue in billion $	2.763	1.700	3.116	3.395
Costs in billion $	2.221	2.221	2.232	2.222
Percentage demand fulfilled	82.3	45.1	90.6	99.2
Port costs in million $	469.456	469.456	469.456	469.456
Fleet costs in million $	883.440	883.440	883.440	883.440
Fuel costs in million $	868.498	868.498	868.498	868.498
Transhipment costs in million $	0	0	10.108	0.492
Average computational time in seconds	0.087	0.155	0.076	0.711

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.541	0.458	0.941	1.369
Revenue in billion $	2.763	1.700	3.116	3.395
Costs in billion $	2.221	1.241	2.175	2.026
Percentage demand fulfilled	82.3	45.1	90.6	99.2
Port costs in million $	469.456	273.520	456.144	432.432
Fleet costs in million $	883.440	488.880	861.480	804.240
Fuel costs in million $	868.498	478.699	847.645	789.247
Transhipment costs in million $	0	0	10.108	0.492
Average computational time in seconds	0.093	0.165	0.077	0.671

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.489	-0.514	0.850	1.147
Revenue in billion $	2.753	1.751	3.158	3.412
Costs in billion $	2.265	2.265	2.308	2.266
Percentage demand fulfilled	81.7	46.4	89.7	99.8
Port costs in million $	494.208	494.208	494.208	494.208
Fleet costs in million $	894.240	894.240	894.240	894.240
Fuel costs in million $	876.217	876.217	876.217	876.217
Transhipment costs in million $	0	0	43.224	0.976
Average computational time in seconds	0.086	0.154	0.077	0.766

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.490	0.438	0.909	1.340
Revenue in billion $	2.753	1.751	3.158	3.412
Costs in billion $	2.264	1.312	2.249	2.072
Percentage demand fulfilled	81.7	46.4	89.7	99.8
Port costs in million $	493.584	298.480	481.520	455.936
Fleet costs in million $	893.880	513.720	870.840	815.760
Fuel costs in million $	876.127	500.161	853.054	799.466
Transhipment costs in million $	0	0	43.224	0.976
Average computational time in seconds	0.089	0.154	0.078	0.737

Table D.2: Results of the case with 3 routes

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.791	0.123	0.409	1.485
Revenue in billion $	1.735	1.067	1.365	2.473
Costs in billion $	0.944	0.944	0.956	0.988
Percentage demand fulfilled	52.7	28.1	39.4	69.8
Port costs in million $	193.440	193.440	193.440	193.440
Fleet costs in million $	378.360	378.360	378.360	378.360
Fuel costs in million $	371.967	371.967	371.967	371.967
Transhipment costs in million $	0	0	11.884	43.872
Average computational time in seconds	0.041	0.084	0.077	0.166

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.791	0.310	0.423	1.485
Revenue in billion $	1.735	1.067	1.365	2.473
Costs in billion $	0.944	0.757	0.942	0.988
Percentage demand fulfilled	52.7	28.1	39.4	69.8
Port costs in million $	193,440	159,120	191,568	193,440
Fleet costs in million $	378.360	301.680	372.600	378.360
Fuel costs in million $	371.967	296.260	366.203	371.967
Transhipment costs in million $	0	0	11.884	43.872
Average computational time in seconds	0.040	0.086	0.077	0.166

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.754	0.259	0.453	1.448
Revenue in billion $	1.705	1.210	1.440	2.426
Costs in billion $	0.952	0.952	0.986	0.978
Percentage demand fulfilled	52.0	31.7	40.7	68.8
Port costs in million $	203.008	203.008	203.008	203.008
Fleet costs in million $	379.440	379.440	379.440	379.440
Fuel costs in million $	369.172	369.172	369.172	369.172
Transhipment costs in million $	0	0	34.832	26.808
Average computational time in seconds	0.039	0.087	0.077	0.173

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.754	0.416	0.478	1.448
Revenue in billion $	1.705	1.210	1.440	2.426
Costs in billion $	0.952	0.794	0.962	0.978
Percentage demand fulfilled	52.0	31.7	40.7	68.8
Port costs in million $	203.008	173.472	198.640	203.008
Fleet costs in million $	379.440	314.640	369.360	379.440
Fuel costs in million $	369.172	305.795	359.439	369.172
Transhipment costs in million $	0	0	34.832	26.808
Average computational time in seconds	0.039	0.089	0.078	0.173

Table D.3: Results of the case with 5 routes

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.764	-0.061	0.939	1.699
Revenue in billion $	2.326	1.502	2.514	3.289
Costs in billion $	1.562	1.562	1.576	1.591
Percentage demand fulfilled	70.0	39.7	72.9	95.4
Port costs in million $	329.472	329.472	329.472	329.472
Fleet costs in million $	622.080	622.080	622.080	622.080
Fuel costs in million $	610.852	610.852	610.852	610.852
Transhipment costs in million $	0	0	13.344	28.140
Average computational time in seconds	0.064	0.121	0.080	0.385

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.766	0.434	0.948	1.700
Revenue in billion $	2.326	1.502	2.514	3.289
Costs in billion $	1.560	1.068	1.567	1.589
Percentage demand fulfilled	70.0	39.7	72.9	95.4
Port costs in million $	328.224	232.128	326.768	328.848
Fleet costs in million $	621.360	422.640	618.480	621.720
Fuel costs in million $	610.674	413.086	607.929	610.763
Transhipment costs in million $	0	0	13.344	28.140
Average computational time in seconds	0.062	0.117	0.077	0.398

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.812	-0.124	0.768	1.725
Revenue in billion $	2.400	1.464	2.391	3.335
Costs in billion $	1.588	1.588	1.623	1.611
Percentage demand fulfilled	71.1	38.7	69.7	96.7
Port costs in million $	339.248	339.248	339.248	339.248
Fleet costs in million $	629.280	629.280	629.280	629.280
Fuel costs in million $	619.615	619.615	619.615	619.615
Transhipment costs in million $	0	0	34.660	22.500
Average computational time in seconds	0.062	0.121	0.078	0.390

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.812	0.443	0.792	1.725
Revenue in billion $	2.400	1.464	2.391	3.335
Costs in billion $	1.588	1.021	1.599	1.611
Percentage demand fulfilled	71.1	38.7	69.7	96.7
Port costs in million $	339.248	227.968	334.880	339.248
Fleet costs in million $	629.280	401.400	619.200	629.280
Fuel costs in million $	619.615	392.067	609.787	619.615
Transhipment costs in million $	0	0	34.660	22.500
Average computational time in seconds	0.062	0.119	0.078	0.405

Table D.4: Results of the case with 10 routes

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	-0.249	-1.450	0.053	0.156
Revenue in billion $	3.019	1.821	3.345	3.419
Costs in billion $	3.150	3.150	3.150	3.150
Percentage demand fulfilled	89.4	48.5	97.7	100.0
Port costs in million $	662.480	662.480	662.480	662.480
Fleet costs in million $	1254.240	1254.240	1254.240	1254.240
Fuel costs in million $	1233.190	1233.190	1233.190	1233.190
Transhipment costs in million $	0	0	0	0
Average computational time in seconds	0.124	0.198	0.077	1.303

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	-0.130	0.455	0.536	1.238
Revenue in billion $	3.019	1.821	3.345	3.419
Costs in billion $	3.150	1.367	2.809	2.181
Percentage demand fulfilled	89.4	48.5	97.7	100.0
Port costs in million $	662.480	296.608	583.648	464.464
Fleet costs in million $	1254.240	540.000	1121.400	866.520
Fuel costs in million $	1233.190	529.985	1103.885	850.271
Transhipment costs in million $	0	0	0	0
Average computational time in seconds	0.117	0.187	0.077	1.296

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	-0.249	-1.450	0.053	0.156
Revenue in billion $	3.014	1.813	3.345	3.419
Costs in billion $	3.263	3.263	3.292	3.263
Percentage demand fulfilled	89.3	48.3	96.3	100.0
Port costs in million $	718.848	718.848	718.848	718.848
Fleet costs in million $	1287.720	1287.720	1287.720	1287.720
Fuel costs in million $	1256.566	1256.566	1256.566	1256.566
Transhipment costs in million $	0	0	28.744	0
Average computational time in seconds	0.122	0.192	0.078	1.383

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	-0.249	0.399	0.502	1.191
Revenue in billion $	3.014	1.813	3.345	3.419
Costs in billion $	3.263	1.414	2.843	2.227
Percentage demand fulfilled	89.3	48.3	96.3	100.0
Port costs in million $	718.848	322.608	610.064	491.920
Fleet costs in million $	1287.720	553.680	1113.840	877.680
Fuel costs in million $	1256.566	537.779	1090.230	857.855
Transhipment costs in million $	0	0	28.744	0
Average computational time in seconds	0.122	0.194	0.078	1.383

Table D.5: Results of the case with 5 ports

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.130	-0.831	0.237	0.307
Revenue in billion $	2.048	1.087	2.160	2.226
Costs in billion $	1.918	1.918	1.923	1.918
Percentage demand fulfilled	92.6	44.1	96.6	99.6
Port costs in million $	333.216	333.216	333.216	333.216
Fleet costs in million $	792.360	792.360	792.360	792.360
Fuel costs in million $	792.645	792.645	792.645	792.645
Transhipment costs in million $	0	0	4.780	0
Average computational time in seconds	0.046	0.069	0.076	0.268

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.130	0.497	0.510	0.955
Revenue in billion $	2.048	1.087	2.160	2.226
Costs in billion $	1.918	0.590	1.650	1.270
Percentage demand fulfilled	92.6	44.1	96.6	99.6
Port costs in million $	333.216	102.544	281.216	222.144
Fleet costs in million $	792.360	242.280	680.760	523.440
Fuel costs in million $	792.645	245.152	683.335	524.688
Transhipment costs in million $	0	0	4.780	0
Average computational time in seconds	0.045	0.070	0.076	0.265

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.065	-0.910	0.167	0.245
Revenue in billion $	2.036	1.060	2.153	2.217
Costs in billion $	1.971	1.971	1.985	1.972
Percentage demand fulfilled	91.9	42.8	96.2	99.3
Port costs in million $	357.968	357.968	357.968	357.968
Fleet costs in million $	811.800	811.800	811.800	811.800
Fuel costs in million $	800.942	800.942	800.942	800.942
Transhipment costs in million $	0	0	14.752	1.132
Average computational time in seconds	0.049	0.073	0.076	0.293

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.065	0.506	0.572	0.969
Revenue in billion $	2.036	1.060	2.153	2.217
Costs in billion $	1.971	0.554	1.581	1.248
Percentage demand fulfilled	91.9	42.8	96.2	99.3
Port costs in million $	357.968	101.296	279.968	229.424
Fleet costs in million $	811.800	226.440	646.920	512.640
Fuel costs in million $	800.942	226.640	638.967	504.437
Transhipment costs in million $	0	0	14.752	1.132
Average computational time in seconds	0.049	0.073	0.077	0.293

Table D.6: Results of the case with 9 ports

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.792	-0.539	1.321	2.017
Revenue in billion $	3.182	1.851	3.717	4.415
Costs in billion $	2.390	2.390	2.396	2.398
Percentage demand fulfilled	74.0	36.8	82.7	99.5
Port costs in million $	603.616	603.616	603.616	603.616
Fleet costs in million $	913.320	913.320	913.320	913.320
Fuel costs in million $	873.552	873.552	873.552	873.552
Transhipment costs in million $	0	0	5.680	7.776
Average computational time in seconds	0.137	0.257	0.078	1.503

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.792	0.298	1.321	2.017
Revenue in billion $	3.182	1.851	3.717	4.415
Costs in billion $	2.390	1.553	2.396	2.398
Percentage demand fulfilled	74.0	36.8	82.7	99.5
Port costs in million $	603.616	406.016	603.616	603.616
Fleet costs in million $	913.320	587.520	913.320	913.320
Fuel costs in million $	873.552	559.453	873.552	873.552
Transhipment costs in million $	0	0	5.680	7.776
Average computational time in seconds	0.133	0.255	0.078	1.492

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.773	-0.564	1.014	1.958
Revenue in billion $	3.238	1.901	3.516	4.426
Costs in billion $	2.465	2.465	2.502	2.468
Percentage demand fulfilled	75.5	37.7	78.3	99.8
Port costs in million $	643.136	643.136	643.136	643.136
Fleet costs in million $	934.200	934.200	934.200	934.200
Fuel costs in million $	887.532	887.532	887.532	887.532
Transhipment costs in million $	0	0	36.748	3.268
Average computational time in seconds	0.142	0.264	0.079	2.003

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.773	0.282	1.021	1.958
Revenue in billion $	3.238	1.901	3.516	4.426
Costs in billion $	2.465	1.620	2.495	2.468
Percentage demand fulfilled	75.5	37.7	78.3	99.8
Port costs in million $	643.136	434.720	641.680	643.136
Fleet costs in million $	934.200	608.040	931.680	934.200
Fuel costs in million $	887.532	576.813	884.994	887.532
Transhipment costs in million $	0	0	36.748	3.268
Average computational time in seconds	0.141	0.266	0.080	1.617

Table D.7: Results of the case with constant revenue

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.402	-0.506	0.567	0.785
Revenue in billion $	1.954	1.046	2.127	2.347
Costs in billion $	1.552	1.552	1.560	1.562
Percentage demand fulfilled	83.2	44.6	90.6	100.0
Port costs in million $	468.832	468.832	468.832	468.832
Fleet costs in million $	215.280	215.280	215.280	215.280
Fuel costs in million $	868.244	868.244	868.244	868.244
Transhipment costs in million $	0	0	7.756	10.112
Average computational time in seconds	0.086	0.156	0.077	0.724

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.402	0.192	0.628	0.897
Revenue in billion $	1.954	1.046	2.127	2.347
Costs in billion $	1.552	0.854	1.499	1.450
Percentage demand fulfilled	83.2	44.6	90.6	100.0
Port costs in million $	468.832	269.984	449.696	437.632
Fleet costs in million $	215.280	120.960	206.640	200.520
Fuel costs in million $	868.244	463.109	835.274	801.522
Transhipment costs in million $	0	0	7.756	10.112
Average computational time in seconds	0.087	0.154	0.077	0.724

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.345	-0.517	0.524	0.765
Revenue in billion $	1.928	1.065	2.150	2.348
Costs in billion $	1.583	1.583	1.626	1.583
Percentage demand fulfilled	82.1	45.4	91.1	100.0
Port costs in million $	487.344	487.344	487.344	487.344
Fleet costs in million $	222.480	222.480	222.480	222.480
Fuel costs in million $	872.940	872.940	872.940	872.940
Transhipment costs in million $	0	0	42.856	0
Average computational time in seconds	0.088	0.160	0.078	0.713

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.345	0.142	0.558	0.896
Revenue in billion $	1.928	1.065	2.150	2.348
Costs in billion $	1.583	0.923	1.592	1.452
Percentage demand fulfilled	82.1	45.4	91.1	100.0
Port costs in million $	487.344	296.608	477.776	449.904
Fleet costs in million $	222.480	132.480	218.160	205.200
Fuel costs in million $	872.940	494.298	853.446	796.879
Transhipment costs in million $	0	0	42.856	0
Average computational time in seconds	0.088	0.161	0.079	0.667

Table D.8: Results of the case with no transhipment costs

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.568	-0.477	0.853	1.239
Revenue in billion $	2.745	1.701	3.030	3.416
Costs in billion $	2.177	2.177	2.177	2.177
Percentage demand fulfilled	82.0	45.4	89.2	99.9
Port costs in million $	456.352	456.352	456.352	456.352
Fleet costs in million $	868.680	868.680	868.680	868.680
Fuel costs in million $	852.140	852.140	852.140	852.140
Transhipment costs in million $	0	0	0	0
Average computational time in seconds	0.079	0.141	0.077	0.615

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.570	0.449	0.881	1.305
Revenue in billion $	2.745	1.701	3.030	3.416
Costs in billion $	2.175	1.252	2.149	2.111
Percentage demand fulfilled	82.0	45.4	89.2	99.9
Port costs in million $	454.896	268.320	449.280	443.456
Fleet costs in million $	867.960	496.440	857.520	842.040
Fuel costs in million $	851.957	486.849	842.020	825.698
Transhipment costs in million $	0	0	0	0
Average computational time in seconds	0.080	0.141	0.077	0.632

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.522	-0.482	0.847	1.187
Revenue in billion $	2.749	1.745	3.074	3.414
Costs in billion $	2.227	2.227	2.227	2.227
Percentage demand fulfilled	81.8	46.4	88.2	99.8
Port costs in million $	480.272	480.272	480.272	480.272
Fleet costs in million $	884.160	884.160	884.160	884.160
Fuel costs in million $	862.519	862.519	862.519	862.519
Transhipment costs in million $	0	0	0	0
Average computational time in seconds	0.089	0.161	0.079	0.703

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.523	0.454	0.876	1.247
Revenue in billion $	2.749	1.745	3.074	3.414
Costs in billion $	2.226	1.292	2.198	2.167
Percentage demand fulfilled	81.8	46.4	88.2	99.8
Port costs in million $	479.648	286.624	473.200	468.000
Fleet costs in million $	883.800	509.040	873.000	859.680
Fuel costs in million $	862.430	495.991	851.842	839.222
Transhipment costs in million $	0	0	0	0
Average computational time in seconds	0.094	0.165	0.083	0.686

Table D.9: Results of the case with double transhipment costs

No hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.538	-0.451	0.933	1.207
Revenue in billion $	2.743	1.754	3.157	3.416
Costs in billion $	2.205	2.205	2.224	2.209
Percentage demand fulfilled	81.4	46.6	91.1	99.9
Port costs in million $	465.296	465.296	465.296	465.296
Fleet costs in million $	876.960	876.960	876.960	876.960
Fuel costs in million $	862.739	862.739	862.739	862.739
Transhipment costs in million $	0	0	19.024	4.008
Average computational time in seconds	0.087	0.156	0.077	0.668

No hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.538	0.442	1.010	1.361
Revenue in billion $	2.743	1.754	3.157	3.416
Costs in billion $	2.205	1.312	2.147	2.055
Percentage demand fulfilled	81.4	46.6	91.1	99.9
Port costs in million $	465.296	287.872	448.032	436.592
Fleet costs in million $	876.960	517.680	847.080	814.320
Fuel costs in million $	862.739	506.451	832.949	800.178
Transhipment costs in million $	0	0	19.024	4.008
Average computational time in seconds	0.088	0.160	0.077	0.678

Hubs, all routes	KWM	PDA	AUH	CAM
Profit in billion $	0.521	-0.545	0.746	1.168
Revenue in billion $	2.768	1.701	3.048	3.419
Costs in billion $	2.246	2.246	2.301	2.251
Percentage demand fulfilled	82.3	45.1	89.0	100.0
Port costs in million $	487.968	487.968	487.968	487.968
Fleet costs in million $	888.120	888.120	888.120	888.120
Fuel costs in million $	870.389	870.389	870.389	870.389
Transhipment costs in million $	0	0	54.976	4.448
Average computational time in seconds	0.086	0.150	0.078	0.730

Hubs, only used routes	KWM	PDA	AUH	CAM
Profit in billion $	0.530	0.404	0.782	1.359
Revenue in billion $	2.768	1.701	3.048	3.419
Costs in billion $	2.237	1.297	2.266	2.060
Percentage demand fulfilled	82.3	45.1	89.0	100.0
Port costs in million $	487.136	294.736	481.728	450.112
Fleet costs in million $	887.760	506.520	877.680	810.720
Fuel costs in million $	862.430	495.991	851.842	794.235
Transhipment costs in million $	0	0	54.976	4.448
Average computational time in seconds	0.089	0.159	0.078	0.678

Appendix E

Best Network

Table E.1: Main routes of the best network

M1	M2	M3	M4	M5	M6
Shenzhen Yantian	Ningbo	Busan	Ningbo	Ningbo	Ningbo
Kaohsiung	Shanghai	Qingdao	Busan	Shanghai	Busan
Xiamen	Liangyungang	Shanghai	Qingdao	Antwerp	Kwangyang
Shenzhen Chiwan	Dalian	Hamburg	Liangyungang	Hamburg	Qingdao
Shenzhen Da Chan Bay	Xingang	Bremerhaven	Shanghai	Bremerhaven	Xingang
Hong Kong	Qingdao	Colombo	Colombo	Algeciras	Dalian
Colombo	Busan	Singapore	Gioia Tauro	Valencia	Liangyungang
Gioia Tauro	Shenzhen Chiwan	Shenzhen Chiwan	Genoa	Barcelona	Shanghai
Valencia	Hong Kong	Hong Kong	Fos	Gioia Tauro	Damietta
Antwerp	Le Havre	Shenzhen Yantian	Barcelona	Port Klang	Port Said
Felixstowe	Felixstowe	Xiamen	Valencia	Tanjung Pelepas	Jeddah
Le Havre	Zeebrugge	Kaohsiung	Malaga	Singapore	Salalah
Rotterdam	Rotterdam	Busan	Tangiers	Laem Chabang	Jebel Ali
Zeebrugge	Bremerhaven		Algeciras	Ningbo	Colombo
Antwerp	Hamburg		Shenzhen Chiwan		Ningbo
Piraeus	Antwerp		Shenzhen Da Chan Bay		
Damietta	Valencia		Hong Kong		
Port Said	Hong Kong		Shenzhen Yantian		
Jeddah	Ningbo		Kaohsiung		
Port Klang			Ningbo		
Tanjung Pelepas					
Singapore					
Vung Tau					
Shenzhen Yantian					

Table E.2: Feeder routes of the best network

Route	Ports visited				
F01	Valencia	Genoa	Valencia		
F02	Valencia	Barcelona	Fos	Valencia	
F03	Valencia	Algeciras	Tangiers	Malaga	Valencia
F04	Hamburg	Aarhus	Gdansk	Gothenburg	Hamburg
F05	Rotterdam	Le Havre	Rotterdam		
F06	Shanghai	Nagoya	Kobe	Shanghai	
F07	Shanghai	Shimizu	Yokohama	Kwangyang	Shanghai
F08	Shanghai	Dalian	Xingang	Qingdao	Shanghai
F09	Shanghai	Liangyungang	Taipei	Fuzhou	Shanghai
F10	Hong Kong	Kaohsiung	Hong Kong		
F11	Hong Kong	Shenzhen Da Chan Bay	Shenzhen Yantian	Xiamen	Hong Kong
F12	Singapore	Vung Tau	Laem Chabang	Singapore	
F13	Port Said	Istanbul Ambarli	Constantza	Port Said	
F14	Port Said	Izmit	Ilyichevsk	Odessa	Port Said
F15	Port Said	Piraeus	Port Said		
F16	Port Said	Koper	Rijeka	Port Said	
F17	Port Said	Trieste	Port Said		

Table E.3: Number of times a port is visited on the main and feeder routes

Port name	Main route	Feeder route	Port name	Main route	Feeder route
Yokohama	0	1	Port Said	2	5
Shimizu	0	1	Damietta	2	0
Nagoya	0	1	Izmit	0	1
Kobe	0	1	Istanbul Ambarli	0	1
Busan	4	0	Odessa	0	1
Kwangyang	1	1	Ilyichevsk	0	1
Dalian	2	1	Constantza	0	1
Xingang	2	1	Piraeus	1	1
Qingdao	3	1	Rijeka	0	1
Liangyungang	4	1	Koper	0	1
Shanghai	5	4	Trieste	0	1
Ningbo	4	0	Gioia Tauro	3	0
Fuzhou	0	1	Genoa	1	1
Taipei	0	1	Fos	1	1
Xiamen	2	1	Barcelona	2	1
Kaohsiung	3	1	Valencia	4	3
Shenzhen Yantian	3	1	Malaga	1	1
Hong Kong	5	2	Algeciras	2	1
Shenzhen Chiwan	4	0	Tangiers	1	1
Shenzhen Da Chan Bay	2	1	Le Havre	2	1
Vung Tau	1	1	Felixstowe	2	0
Laem Chabang	1	1	Zeebrugge	2	0
Singapore	3	1	Antwerp	4	0
Tanjung Pelepas	2	0	Rotterdam	2	1
Port Klang	2	0	Bremerhaven	3	0
Colombo	4	0	Hamburg	3	1
Jebel Ali	1	0	Gothenburg	0	1
Salalah	1	0	Aarhus	0	1
Jeddah	2	0	Gdansk	0	1

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