Designing liner shipping networks

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Abstract

In this paper the combined fleet-design, ship-scheduling and cargo-routing problem with limited availability of ships in liner shipping is considered. A genetic algorithm based solution method is proposed in which the ports are first aggregated into port cluster to reduce the problem size. When the cargo flows are disaggregated, a feeder service network is introduced to ship the cargo within a port cluster. The solution method is tested on a problem instance containing 58 ports on the Asia-Europe trade lane of Maersk. The best obtained profit gives an improvement of almost 20% compared to the reference network based on the Maersk network.

Keywords: Transportation, liner shipping, network design, scheduling

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.

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 these 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 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. In a sequel, Ronen (1993) provides a detailed summary of published research on ship scheduling and related problem in the period from 1983-1993. Next, the survey of Christiansen et al. (2004) describes the major developments in the ship routing and scheduling problems in the period from 1994-2004. Finally, Wang and Meng (2011) give an overview of the most important existing literature on liner shipping studies and propose directions for further research.

Little research is performed on the determination of the optimal fleet design. Fagerholt (1999) develop a 3-phase solution approach to optimize the fleet size in liner shipping networks in which all feasible routes are generated and combined. Thereafter, the optimal fleet size is determined using a set partitioning problem, which is also solved in this phase. 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. Both models become time consuming when the problem becomes larger.

Song et al. (2007) discuss a cargo allocation model with two objectives. 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.

Most research is related to the combined ship-scheduling and cargo-routing problem. First, Rana and Vickson (1991) and Fagerholt (2004) present integer programming problems to solve the combined ship-scheduling and cargo-routing problem. They are able to solve small instances in a reasonable amount of time, but for larger instances their methods become too time consuming.

Next, some research exists in which mathematical programming methods, like Benders decomposition, are used to solve the combined ship-scheduling and cargo-routing problem (see for example Agarwal and Ergun (2008), Álvarez (2009) and Gelareh and Pisinger (2011)). These methods can be used to solve some very small instances to optimality, but for larger instances heuristical methods are still needed.

1.2 Objective

The objective of this study is to develop a service network in liner shipping. The service network should consist of a set of routes, the allocation of ships to the routes, the sailing speed of the ships on each route and the allocation of cargo over the routes. In other words, our goal is to solve the fleet-design, ship-scheduling and cargo-routing problems simultaneously, where we consider the case with limited availability of ships. Since the combined fleet-design, ship-scheduling and cargo-routing problem is too large to solve efficiently, we choose to aggregate the ports in the model and use a genetic algorithm based method to solve the problem. Thereto, we construct a model that is able to optimally allocate the cargo to the available ships, when the ship schedules are known. Thereafter, the aggregated ports have to be disaggregated. To do this, we introduce feeder service to ship the cargo between the central port in a port cluster and all other ports of the same cluster. Furthermore, we propose a method that generates initial feasible ship schedules and computes the associated optimal cargo allocation and profit. Then, the genetic algorithm will generate new feasible ship schedules and this process will be repeated until a certain stopping criteria is met.

2 Problem formulation

We consider the combined fleet-design, ship-scheduling and cargo-routing problem with limited availability of ships. In this section, first the three individual problems are described. Thereafter, a formulation of the combined problem is given.

2.1 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.

2.2 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).

2.3 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. Our goal is to maximize the profit for one shipping company, so competition is not investigated. 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 other cargos have to be transhipped to other routes. All these decisions are made in the cargo-routing problem.

2.4 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. In this research, we limit the available ships that we can use in the service network. Therefore, we only try to select the best ships out of the available ships instead of solving the fleet-design problem from scratch.

3 Model formulation

In this section, we discuss the methods used to solve the combined fleet-design, ship-scheduling and cargo-routing problem. First, we propose the linear programming model that can be used to solve the cargo-routing problem. Next, we explain the methods used to aggregate and disaggregate the ports. Thereafter, we discuss the method used to construct the initial service networks. Finally, we propose an algorithm to change the existing service networks in order to improve them.

3.1 Cargo Allocation Model (CAM)

The cargo-routing problem can be formulated as a linear programming problem. To do this, we introduce the following sets:

$h \in \mathcal{H}$	set of harbors
$t \in \mathcal{T}$	set of transhipment harbors
$s \in \mathcal{S}$	set of ship routes

The following parameters are used in the model:

r_{h_1,h_2}	Revenue of transporting one TEU from harbor h_1 to harbor h_2
c_t^t	Cost of transhipping one TEU in transhipment harbor t
c_h^h	Cost of (un)loading one TEU in origin or destination harbor h
d_{h_1,h_2}	Demand with origin harbor h_1 and destination harbor h_2
b_s	Capacity on ship route s
$I^{path}_{h_1,h_2,h_3,h_4,s}$	0/1 parameter that takes the value 1 if a ship passes consecutive harbors h_3 and h_4 when sailing from harbor h_1 to harbor h_2 on ship route s
$I^{cycle}_{h_1,h_2,s}$	0/1 parameter that takes the value 1 if a ship passes both harbors h_1 and h_2 on ship route s
$I^{cons}_{h_1,h_2,s}$	0/1 parameter that takes the value 1 if harbor h_2 is directly visited after harbor h_1 on ship route s

In the model formulation, we distinguish between direct flows and transhipment flows. Direct flows are cargo flows between the origin and destination harbor of a demand pair for which no transhipment movement has to be made. Cargo flows for which transhipment movements are necessarily are called transhipment flows. Now, we introduce the following decision variables:

$x_{h_1,h_2,s}$	Cargo flow on ship route s between consecutive harbors h_1 and h_2
$x^{od}_{h_1,h_2,s}$	Direct cargo flow on ship route s between harbors h_1 and h_2
$x^{ot}_{h_1,t,h_2,s}$	Transhipment flow on ship route s between harbor h_1 and transhipment harbor t with destination harbor h_2
x^{td}_{t,h,s_1,s_2}	Transhipment flow on ship route s_2 between transhipment harbor t and destination harbor h, where the flow to transhipment harbor t was transported on ship route s_1
$x^{tt}_{t_1,t_2,h,s_1,s_2}$	Transhipment flow on ship route s_2 between transhipment harbor t_1 and transhipment harbor t_2 with destination harbor h, where the flow to transhipment harbor t_1 was transported on ship route s_1
$x^{tot}_{h_1,h_2,s}$	Total cargo flow on ship route s between harbors h_1 and h_2

Now, we can give the linear programming formulation.

$$\begin{aligned} \max \quad & \sum_{h_1,h_2,s} r_{h_1,h_2}\left(x^{od}_{h_1,h_2,s} + \sum_{t} x^{ot}_{h_1,t,h_2,s}\right) \\ & -\sum_{h_1} c^h_{h_1}\left(\sum_{t,h_2,s}\left[x^{ot}_{h_1,t,h_2,s} + x^{ot}_{h_2,t,h_1,s}\right] + \sum_{h_2,s}\left[x^{od}_{h_1,h_2,s} + x^{od}_{h_2,h_1,s}\right]\right) \\ & -\sum_{t_1} c^t_{t_1}\left(\sum_{t_2,h_2,s_1,s_2} x^{tt}_{t_1,t_2,h_2,s_1,s_2} + \sum_{h_2,s_1,s_2} x^{td}_{t_1,h_2,s_1,s_2}\right) \qquad (1) \end{aligned}$$

subject to

$$\sum_{t,s} x^{ot}_{h_1,t,h_2,s} + \sum_{s} x^{od}_{h_1,h_2,s} \leq d_{h_1,h_2} \qquad \forall h_1, h_2 \qquad (2)$$

$$x_{h_1,h_2,s} \leq b_s \qquad \forall h_1, h_2, s, I^{cons}_{h_1,h_2,s} = 1 \qquad (3)$$

$$\begin{aligned} & \sum_{h_1} x^{ot}_{h_1,t_1,h_2,s_1} + \sum_{t_2,s_2} x^{tt}_{t_2,t_1,h_2,s_2,s_1} \\ & \quad -\sum_{s_2} x^{td}_{t_1,h_2,s_1,s_2} - \sum_{t_2,s_2} x^{tt}_{t_1,t_2,h_2,s_1,s_2} = 0 \qquad \forall t_1, h_2, s_1, I^{cycle}_{h1,h2,s} = 1 \qquad (4) \end{aligned}$$

$$x_{h_1,h_2,s} - \sum_{h_3,h_4} x^{tot}_{h_3,h_4,s} I^{path}_{h_3,h_4,h_1,h_2,s} = 0 \qquad \forall h_1, h_2, s, I^{cons}_{h_1,h_2,s} = 1 \qquad (5)$$

$$\begin{aligned} & x^{tot}_{h_1,h_2,s_1} - x^{od}_{h_1,h_2,s_1} - \sum_{h_3} x^{ot}_{h_1,h_2,h_3,s_1} \\ & \quad -\sum_{s_2} x^{td}_{h_1,h_2,s_2,s_1} - \sum_{h_3,s_2} x^{tt}_{h_1,h_2,h_3,s_2,s_1} = 0 \qquad \forall h_1, h_2, s_1 \qquad (6) \end{aligned}$$

$$x_{h_1,h_2,s} \geq 0 \qquad \forall h_1, h_2, s, I^{cons}_{h_1,h_2,s} = 1 \qquad (7)$$

$$x^{od}_{h_1,h_2,s} \geq 0 \qquad \forall h_1, h_2, s \qquad (8)$$

$$x^{td}_{t,h,s_1,s_2} \geq 0 \qquad \forall h, t, s_1, s_2, I^{cycle}_{t,h,s_2} = 1 \qquad (9)$$

$$x^{ot}_{h_1,t,h_2,s} \geq 0 \qquad \forall h_1, h_2, t, s, I^{cycle}_{h_1,t,s} = 1 \qquad (10)$$

$$x^{tt}_{t_1,t_2,h,s_1,s_2} \geq 0 \qquad \forall h, t_1, t_2, s_1, s_2, I^{cycle}_{t_1,t_2,s_2} = 1 \qquad (11)$$

The objective (1) of the cargo allocation problem is to maximize total profit. Profit is given by the revenue minus the costs. The costs only consist of (un)loading cost and transhipping cost, because the route network is given, so all other costs are fixed and can be subtracted afterwards.

Constraints (2) ensure that the total cargo shipped from one port to another does not exceed the demand of that port combination. Next, Constraints (3) make sure that the total load of a ship between each two consecutive harbors does not exceed the capacity of the ship. Constraints (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 harbor h_2. In other words, they make sure that all flow unloaded to be transhipped, will also be loaded on another route. Constraints (5) define the the amount of flow between two consecutive ports and Constraints (6) define the total flow between each two ports in the same cycle. Finally, Constraints (7)-(11) guarantee a nonnegative flow between each two ports.

3.2 Aggregation of ports

When the problem instance becomes larger, the computational time of the cargo allocation model increases exponentially. Thus, 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 CAM model to which number of ports the problem has to be reduced.

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 (the port of the cluster where ships will make their port visit). Finally, the data of individual ports have to be aggregated to port cluster data.

First, the method used to determine the ports that are aggregated into the same cluster is considered. Ports are aggregated based on their mutual 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. To avoid problems, we compare the distance of a port that we will add to the cluster with the central port. Thus, first the central port of the cluster has to be determined. Thereto, we first make a list containing ports that should be central ports based on their expected yearly throughput. Furthermore, a list of ports that are not allowed to be central ports (noncentral ports) and a list with all remaining (intermediary) ports are made. These lists can now be used to design the clusters as will be explained in the remainder of this section.

First, for each harbor on the central port list a cluster is created. The harbors of the other two list that are within the maximum distance to their closest central port are added to the corresponding cluster. If there are intermediary ports remaining that are not yet added to one of the clusters, a new cluster is created for the largest intermediary port, which becomes a central port. All intermediary and noncentral ports that are closest to this port (compared to the other central ports) and within the maximum distance are added to this new cluster (if a port was already allocated to one of the other clusters, it is removed from this old cluster). This is repeated until all intermediary ports are allocated to a cluster. Finally, if there are still some noncentral ports remaining, they are allocated to the cluster they are closest to. Note that in this last step 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 using liner services.

Now, we have to aggregate the individual port data into port cluster data. 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.

3.3 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 cargo flow between each pair of clusters is obtained from the CAM model. Now, we can determine the ports belonging to these clusters. For each port pair with origin port in the origin cluster and destination port in the destination cluster, we can determine the revenue of transporting cargo between these ports. Furthermore, we know the demand between these two ports. Then, the disaggregation is done by repeatedly allocating as much cargo as possible to the port pair with the highest revenue until the total cargo flow is allocated. 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 port clusters of the cargo allocation model.

When all combinations are considered and the cargo allocation between each two real ports is 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.

3.3.1 Reducing the size of a feeder service

When we start, 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.

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.

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.

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.

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 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.

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.

3.3.2 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 feeder handling costs will also not change. Because the costs on the main route will also stay the same, the only changes will occur in the feeder capital, operating and fuel costs. Finding a profitable exchange corresponds now to finding an exchange for which these feeder costs are reduced.

We will explain the method used to exchange ports 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.

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.

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 feeder costs. Thereafter, the new determined capacities can be used to calculate the new feeder costs of both services. Finally, the increase in profit of this exchange can be calculated by subtracting the sum of the feeder costs of the new feeder services F_1 and F_2 from the initial feeder costs.

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.

3.3.3 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.

3.3.4 Add ports to main route

Next, we investigate 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 also have 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 is performed once before and once 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.

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.
   (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.

The algorithm describes the main idea of the method used. 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.

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 unused capacity of the ship on the additional legs. To determine how much cargo can be reallocated according to the unused 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 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 instead of in the central port of the cluster. Thus, in flow F_1 the cargo flow to port N is included while 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 $N_{in} \leq Cap - F + N_{out}$.

Port N is visited after the center of the cluster

Port N is visited before the center of the cluster

Figure 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.

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}).

In step 6 the real changes are made. First, we determine 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.

4 Designing an initial liner shipping network

To design an initial liner shipping network, we assume that ports are visited in their geographical order. Thereafter, we generate initial routes and determine the optimal speed on each route.

4.1 Generate initial routes

Initial routes are generated at random. First, we determine randomly the number of routes in the network between a minimum and maximum. Thereafter, for each route in the network, a cluster is called with a certain probability. Thus, we determine in geographical order at random whether a cluster will be visited. The routes obtained using this method are not always feasible routes. The routes have to satisfy three conditions to be feasible.

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.

Finally, a ship type is allocated to the ship route. Thereto, we select randomly a ship type at the set of available ship types. Note that this set has to be updated when the last available ship of a certain type is allocated to a route. In this case, the ship type is removed from the set of available ship types.

Using the above procedure a network is obtained with a random number of feasible 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.

4.2 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. If the time needed to perform one round tour at minimum speed exceeds the maximum route duration, the optimal speed when sailing the route in the maximum duration and the corresponding costs at this speed are calculated instead. Save the total costs and the speed. Thereafter, reduce the number of weeks with one as long as 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.

5 Design a new route network

The following operators are used to change the route network: elitism, selection, crossover and mutation.

5.1 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.

5.2 Selection

In the genetic algorithm based method, networks are selected based on their performance. The selection step can be done in several ways. We use the roulette wheel selection method to select the networks. The selection probability of a network is defined as the relative profit with respect to the total profit in all networks in the set. If some of the networks have negative profits, all profits will be increased to obtain only positive profits. The selected network will be used in the crossover or mutation step.

5.3 Crossover

When two networks are selected, the crossover operator can be used to recombine these two networks into two new networks. We consider two different crossover methods: uniform and route crossover. Next, these crossover methods will be explained.

In the uniform crossover methods, two completely new route networks are created. First, two existing networks are selected. Each network consists of $R\left(2C-1\right)$ 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 $\left(r,c\right), r \leq R, c \leq 2C-1$ the value of the selected combination is with equal probability exchanged between the two selected networks or not exchanged. Similar, the capacities of the routes are with equal probability exchanged or not. Finally, the routes are made feasible using the method earlier described and it is checked whether the ship types allocated to the routes in the networks still satisfy the available fleet constraint.

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. We randomly select a cut point, after which the routes including capacities of the two selected networks are exchanged. 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. However, the fleet composition of the networks can violate the available fleet constraint. Thus, we check whether this happens and exchange route with allocated ships where necessarily.

5.4 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.

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, still available, 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.

6 Case study

We apply the proposed algorithm to design a service network that consists of 58 ports on the Asia-Europe trade lane. Most data is based on the service network of Maersk on the Asia-Europe trade lane during spring 2010. Demand is estimated using port throughput data and data obtained from the annual reports of Maersk. Costs for different types of ships and sailing speeds are estimated using data obtained from Lachner and Boskamp (2011), Francesetti and Foschi (2002) and Notteboom (2006). The data can be found in Appendix A.

6.1 Reference network

We define a reference network to which the best obtained networks (i.e. the networks with highest profits) can be compared. This will give some information on the performance of the obtained networks. The routes of the reference network can be found in Appendix B

The original Maersk route network, on which the data is based is used as reference network. The network consist of nine routes. On each route a few ships with different capacities are sailing to serve the demand. In our study, a route is served by ships of the same size and each ship size is a multiple of 1000 TEU. Therefore, we round the average capacities of the ships used on a route of the Maersk service network to the nearest multiple of 1000 TEU that is larger than the average to obtain the capacities of the reference network. The profit of the reference network is 1.876 billion USD.

6.2 Characteristics of the best networks

Table 1 shows the overall characteristics of the reference network and the best network obtained using the described method. The best network results in a profit of 2.058 billion USD, which is an increase of 20.6% compared to the reference network. The increase in profit is the result of a cost reduction. The total demand delivered and the revenue in the best network are a little lower than in the reference network, but the routes are more cost efficient. Note that we only consider ship-related costs and revenues in this model. In reality, liner shipping companies will also face other types of costs. However, it is difficult to estimate these non-ship-related costs, so we leave them out of consideration here. Furthermore, we only use estimates on demand, revenue and costs in this research. Since these data are highly sensitive to fluctuations, the increase in profit can change over time.

	Reference network	Best network
Profit in billion USD	1.707	2.058
Revenue in billion USD	7.015	6.920
Cost in billion USD	5.307	4.862
Fraction demand delivered	0.832	0.822
Computational time in seconds	215.7	103.9

Table 1: Comparison of the best network with the reference network

Table 2 shows some characteristics of the best network and the reference network. Note that the total distance traveled in the best network is a bit higher than in the reference network. This can be explained in the following way. The main routes are constructed for only ten port clusters, 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 will be higher when less port clusters are included. However, by using feeder services, ports can be visited more efficiently, which results in less distance that has to be covered, so the

	Reference network	Best network Main	Feeder
Capital and operating cost in billion USD	1.150	1.016	0.073
Fuel cost in billion USD	1.453	1.282	0.079
Port cost in billion USD	0.189	0.161	0.011
Handling cost in billion USD	1.972	1.949	0.027
Transhipment cost in billion USD	0.544	0.016	0
Total cost in billion USD	5.307	4.424	0.044
Fleet size	91	79	16
Number of routes	9	8	16
Average number of port per route	16.4	15.5	3.625
Distance traveled in nm	191,754	167,876	28,692

Table 2: Characteristics of the networks

difference in distance between the two networks is only small.

It follows from Table 2 that the largest cost reduction is obtained in the transhipment cost compared to the reference network. By clustering ports, less ports are included in the main route network and thus less transhipment movements are needed. The capital, operating, fuel and port costs are all reduced a little compared to the reference network.

Compared to the reference network, the number of ships decreases, because the use of a feeder network leads to a more efficient use of ships. In the best network, only eight routes are included compared with nine in the reference network. Since, the number of ships needed for a route equals the round tour time, this will already lead to a significant reduction in the fleet size. The feeder services are all designed in such a way that they will have a round tour time of one week, so only one ship per feeder service is needed.

The computational times are given in seconds for the reference network and in seconds per iteration for the best networks with ten, twelve and fifteen clusters. In one iteration, the profit of all twenty route networks in the set is determined and a new set is made.

6.3 Best network

The routes of both the main and the feeder network of the best obtained route network can be found in Appendix D. The reference network only consists of a main route network, so all ports are at least once visited on a main route. However, not all ports are visited on a main route in the best network. First, the ports in Japan 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 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.

Many ports 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.

Finally, some ports, for example Fuzhou and Taipei, are not visited on the main route because they are relatively small. 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, since they are small ports, the additional costs incurred by adding them to a main route, will probably not be covered by the decrease in feeder costs.

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 deviations 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.

We explain both categories using an example. The first category contains deviations that are forced by the cluster design. For example, in the best network one of the routes visits on the westbound trip first Antwerp and thereafter respectively Zeebrugge, Rotterdam, Le Havre and Felixstowe. When these ports are visited according to geographical order, one would expect that the order would be: Le Havre-Felixstowe-Zeebrugge-Antwerp-Rotterdam. However, this order cannot be obtained in the model, because Le Havre, Felixstowe and Zeebrugge 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, Felixstowe and Zeebrugge have to be placed before Antwerp, which does not belong to the same cluster.

The second category consists of deviations that are caused by the cargo flows. For example, on one of the routes first Ningbo is visited and thereafter respectively Qingdao, Liangyungang and Shanghai. All these ports belong to the cluster with central port Shanghai. The geographical order would be 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. We have 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 would be after Shanghai, it can be more profitable to visit Ningbo before Shanghai when much cargo with destination Ningbo is on the ship.

7 Conclusion

In this study methods to solve the combined fleet-design, ship-scheduling and cargo-routing problem are developed. Thereto, first a linear programming formulation (CAM model) is introduced that can be used to solve the cargo-routing problem to optimality.

However, the computational time of the 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 our study, ten 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, they have to be disaggregated again in individual port results. Some methods are developed and explained in this study. 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, we try to decrease the ship capacities on the feeder services 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.

The best network found using the overall model gives an improvement of about 20% compared to the reference network. The increase in profit is the result of a cost reduction obtained when integrating liner shipping network design. However, since we only consider ship-related costs and revenues and the data is highly sensitive to fluctuations, the profits of the liner shipping company for both the reference network and the best network will be lower in reality. The percentage of improvement will then also be lower.

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. There are basically three possible reasons for this. 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 existence 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 central port and vice versa.

Only intra-regional demand is considered in this study, 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. 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.

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A Data

Ports

The ports considered in this study 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 3.

Distance

The distances between ports can be computed using distance calculators on the internet. The distances between the port combinations can be found in table 4.

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. The demand data is obtained from Lachner & Boskamp (2011). First, 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. Thereafter, 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 6.

Revenue

The revenue data is also obtained from Lachner & 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 & Boskamp obtained the revenue by taking the 10-year average of historical data. This calculation gives the revenue in USD/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 USD/nm in eastbound direction and 0.1677 USD/nm in westbound direction.

Available ships

In Francesetti & 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 study. 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 & Foschi (2002). The available ship sizes for both the main and feeder services can be found in tables 8 and 9. In this study, it is assumed that an unlimited number of feeder ships is available.

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 study. 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 study.

Further, it is assumed that feeder ships sail at a constant speed. This speed is assumed to be 22 nautical miles per hour.

Capital and operating cost

In Francesett & 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 study, that are not given in Francesetti & 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 Fraccesetti & Foschi (2002) for inflation.

An overview on the yearly capital and operating costs per ship size can be found in tables 8 and 9.

Fuel cost

The fuel consumption in ton per day is given for the different ship sizes in Francesetti & 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 USD/ton to obtain the fuel cost in USD per nautical mile for the different ship sizes. In this study an oil price of 500 USD per ton is used in the calculations.

In Notteboom (2006) a figure is given that 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, this figure can be 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 USD per nautical mile for the other sailing speeds of the considered ships.

In table 10 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 9.

Port, (un)loading and transhipment cost

The port, (un)loading and transhipment cost are obtained from Lachner & 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 study, ships are charged 25,000 USD per port visit on a main route and 15,000 USD per port visit on a feeder route. Thus, when a port is visited on a main route $52 \cdot 25,000 = 1,300,000$USD is charged, because each route is performed once a week. For feeder routes, the port cost per year equals $52 \cdot 15,000 = 780,000$USD.

(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 USD per TEU on main routes and 125 on feeder routes. A transhipment consist of a unloading and a loading movement, so the cost of a transhipment is $2 \cdot 175 = 350$USD 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.

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 & Boskamp (2011). In this study, 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 access, maritime passages and chance (Notteboom (2006)). Chance includes weather conditions and mechanical problems. In this study, 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.

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

Table 3: List of ports

Destination Origin	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

Table 4: Distances between ports

Destination **Origin**	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 5: Distances between ports (2)

Destination **Origin**	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

Table 6: Demand between ports

Destination Origin	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 7: Demand between ports (2)

Ship Name	Ship Capacity (TEU)	Total Capacity (TEU/year)	Capital Cost ($/year)	Operating Cost ($/year)	Nr available
M1	4000	208000	4500000	3600000	5
M2	5000	260000	5400000	4050000	5
M3	6000	312000	6000000	4350000	5
M4	7000	364000	6500000	4600000	5
M5	8000	416000	7000000	4850000	5
M6	9000	468000	7500000	5100000	5
M7	10000	520000	8000000	5350000	2
M8	14000	728000	10000000	7850000	1

Table 8: Liner 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

Table 9: Feeder ship characteristics

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

Table 10: Fuel cost for different speeds and ship sizes

B Reference network

Table 11 shows the routes in the reference network during spring 2010. Next, Table 12 shows the different types of ships used on each of the routes.

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 11: Routes in 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

Table 12: Ships and capacities on the Maersk network

C Cluster design

Table 13 shows the composition of the ten clusters obtained after aggregation in this study.

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				

Table 13: Design of the ten clusters

D Best Network

M1	M2	M3	M4
Shenzhen Yantian	Tanjung Pelepas	Busan	Busan
Shenzhen Chiwan	Port Klang	Qingdao	Shanghai
Hong Kong	Singapore	Liangyungang	Shenzhen Yantian
Xiamen	Colombo	Shanghai	Hong Kong
Kaohsiung	Barcelona	Tanjung Pelepas	Singapore
Colombo	Valencia	Singapore	Port Klang
Jebel Ali	Malaga	Port Klang	Felixstowe
Salalah	Tangiers	Jeddah	Rotterdam
Gioia Tauro	Algeciras	Port Said	Antwerp
Barcelona	Antwerp	Damietta	Salalah
Valencia	Zeebrugge	Zeebrugge	Jebel Ali
Algeciras	Rotterdam	Rotterdam	Colombo
Antwerp	Le Havre	Bremerhaven	Busan
Zeebrugge	Felixstowe	Hamburg	
Rotterdam	Tanjung Pelepas	Algeciras	
Le Havre		Valencia	
Felixstowe		Salalah	
Antwerp		Jebel Ali	
Algeciras		Busan	
Valencia			
Gioia Tauro			
Shenzhen Yantian			
10000 TEU	9000 TEU	8000 TEU	7000 TEU

M5	M6	M7	M8
Ningbo	Shenzhen Yantian	Ningbo	Shenzhen Yantian
Qingdao	Shenzhen Chiwan	Qingdao	Shenzhen Chiwan
Busan	Kaohsiung	Liangyungang	Hong Kong
Xingang	Xiamen	Shanghai	Jeddah
Dalian	Shenzhen Da Chan Bay	Colombo	Port Said
Shanghai	Hong Kong	Le Havre	Damietta
Gioia Tauro	Colombo	Zeebrugge	Colombo
Barcelona	Gioia Tauro	Rotterdam	Port Klang
Valencia	Valencia	Felixstowe	Tanjung Pelepas
Algeciras	Algeciras	Damietta	Singapore
Antwerp	Hamburg	Port Said	Shenzhen Yantian
Felixstowe	Bremerhaven	Jeddah	
Zeebrugge	Rotterdam	Shenzhen Chiwan	
Rotterdam	Le Havre	Hong Kong	
Bremerhaven	Zeebrugge	Shenzhen Yantian	
Hamburg	Felixstowe	Ningbo	
Algeciras	Shenzhen Yantian		
Valencia			
Ningbo			
14000 TEU	9000 TEU	9000 TEU	8000 TEU

Table 14: Main routes of the best network

Route	Capacity	Ports visited					
F01	2500	Valencia	Algeciras	Genoa	Fos	Barcelona	Valencia
F02	1250	Valencia	Tangiers	Malaga	Gioia Tauro	Valencia	
F03	2250	Hamburg	Aarhus	Gdansk	Gothenburg	Hamburg	
F04	800	Rotterdam	Zeebrugge	Felixstowe	Le Havre	Rotterdam	
F05	2500	Shanghai	Kwangyang	Busan	Kobe	Nagoya	Shanghai
F06	2250	Shanghai	Yokohama	Dalian	Shanghai		
F07	2500	Shanghai	Xingang	Qingdao	Shanghai		
F08	200	Shanghai	Shimizu	Shanghai			
F09	2000	Shanghai	Liangyungang	Taipei	Fuzhou	Ningbo	Shanghai
F10	1500	Hong Kong	Shenzhen Da Chan Bay	Shenzhen Chiwan	Kaohsiung	Xiamen	Hong Kong
F11	2000	Singapore	Laem Chabang	Singapore			
F12	800	Singapore	Port Klang	Vung Tau	Singapore		
F13	1000	Port Said	Constantza	Odessa	Ilyichevsk	Port Said	
F14	4000	Port Said	Piraeus	Izmit	Istanbul Ambarli	Port Said	
F15	200	Port Said	Rijeka	Port Said			
F16	700	Port Said	Trieste	Koper	Port Said		

Table 15: Feeder routes of the best network