Will liner ships make fewer port calls per route?

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Abstract

Traditional liner shipping route networks consists of many port calls per route. However, container ship sizes have increased substantially over the past few years. These large container ships benefit from economies of scale at sea, but might suffer diseconomies of scale in ports. Therefore, we investigate whether larger container ships will lead to fewer port calls per route. First, we discuss the influence of fewer port visits on some aspects that are difficult to include in a mathematical analysis. Thereafter, we propose a mathematical approach to obtain networks with fewer port calls per route. Liner shipping route networks are generated by distinguishing between hub routes and regional routes. Hub routes are used to connect a small number of hubs, while regional routes connect all other ports with its nearest hub. An iterative approach is used to generate networks, which are evaluated using a mixed integer program in which the joint ship allocation and cargo routing is solved. A case study is performed with different combinations of seven hub ports. In the case study, three capacity scenarios are considered: low, base and high capacity. Our networks generate profits that are more than 25% higher compared with the best known networks in literature.

1 Introduction

The growth in container trade has led to substantial increases in container ship sizes. Larger ships are well known to benefit from economies of scale at sea, but they may suffer from diseconomies of scale in ports. Cullinane and Khanna (1999) performed a study to investigate the (dis)economies of scale in large container ships both in port and at sea. They considered container ships varying in capacity from 200 to 8,000 TEU. Their findings show that diseconomies in ports exist for ships larger than 1,500 TEU, but that the magnitude is quite small. Furthermore, they show that economies of scale at sea exist at least for ships up to 8,000 TEU and the economies of scale at sea clearly outweigh the diseconomies of scale in ports. Although the data used by the authors is outdated, the general observations will most probably still be valid.

The increase in container ship size also has its consequences for the network structure in liner shipping. Not all ports are capable of handling large container ships. Furthermore, it might not be profitable to call at relatively low-demand ports with large-size container ships. Therefore, traditional liner networks consisting of so-called circular, butterfly and pendulum routes may shift to more hub-and-feeder like networks. In circular routes, ports are all visited exactly once on each rotation, while in butterfly routes ports can be called at twice or more during a rotation. Pendulum routes are a special type of butterfly routes in which the same ports are called at on the east- and westbound trip, only in reversed order. Hub-and-feeder networks consist of a small number of large hub ports, which are connected to each other. All other (smaller) ports in the networks are called spokes or feeder ports and are only visited on routes originating from and destined for their closest hub. In South America, shipping routes have recently been reconstructed towards networks similar to hub-and-spoke networks. Furthermore, non-stop services between regions with high demand have been introduced (Sanchez and Wilmsmeier 2011).

Call sizes at terminals have increased as well, as a consequence of the total growth in container trade. This poses problems for terminals, as they face a larger peak load for the stack. Yet larger call sizes on bigger ships also benefit terminal quay crane productivity as cranes can work longer on a bay.

All in all, this raises the question whether container carriers should reduce the number of port visits on a string in order for terminals to be more productive and reduce unproductive port time. In this research, we will also investigate whether a change to hub-and-feeder networks is to be anticipated. Next, we will review literature; first, we will literature related to hub-and-feeder networks and thereafter literature related to traditional liner shipping networks.

Fagerholt (2004) considers the problem of determining the optimal regional network design. The proposed solution approach consists of two stages. First, all feasible routes are generated and then an integer programming problem is solved to select the optimal routes from the set of feasible routes. Our regional network design solution approach is based on this approach.

Imai et al. (2009) examined the profitability of two different types of service networks under several scenarios. They compared a multi-port network with conventional ship sizes with a hub-and-spoke network with mega-ships. The research shows that multi-port networks are more profitable than hub-and-spoke networks except for European shipping companies serving the Asia-Europe trade lane. The hub-and-spoke model in Imai et al. (2009) only allows for direct feeder routes between the hub and the other ports. In our networks, multiple port calls on a feeder route are allowed, which will most probably increase the profitability of a hub-and-spoke network. Further, Imai et al. (2009) use different cost structures and ship types for the multi-port and hub-and-spoke networks. In our research, we will show that even with the same cost structures and ship types, hub-and-spoke systems can be more profitable than multi-port networks. Furthermore, Hsu and Hsieh (2007) consider a ship allocation, sailing frequency and cargo routing problem on a predefined hub-and-spoke network. A two-objective model is used for which Pareto optimal solution curves are presented. The authors compare the performance of the network when cargo is routed directly from a feeder origin port to the destination port with the performance when the cargo is routed via a hub. For some ports direct shipping is preferred over shipping via a hub, while for other ports routing via a hub is less costly.

Gelareh and Pisinger (2011), Gelareh et al. (2013) and Zheng et al. (2015) use mixed integer programming models to formulate the simultaneous hub location, feeder port allocation, fleet deployment and network design problem. In both Gelareh and Pisinger (2011) and Gelareh et al. (2013), networks can contain only one hub route visiting all hubs exactly once. Furthermore, in Gelareh and Pisinger (2011) only direct feeder services are allowed, but feeder ports can be connected to multiple hubs. In Gelareh et al. (2013) multiple feeder ports can be visited on one feeder route, but each feeder port is only visited exactly once in the network. Respectively, a Benders and a Lagrangian decomposition approach are proposed in these works to solve problems that cannot be solved using existing solvers. Zheng et al. (2015) solve the problem using a genetic algorithm embedded with a multi-stage decomposition approach. The latter three papers do not give any indication of whether hub-and-feeder systems are better than multi-port networks.

In the previous works, the determination of which ports are used as hubs and the allocation of the other ports to the hubs are both incorporated in the mixed integer programming model. In Mulder and Dekker (2014) on the contrary, hub selection and port allocation are solved as separate problems before considering the network design and fleet deployment problems. Thereafter, the network design and fleet deployment problem is solved using a genetic algorithm approach. This work is comparable to the work in Mulder and Dekker (2014) as it uses the same idea: we first cluster ports before considering the network design problem. However, this research uses an improved formulation of the cargo routing problem, leading to better solutions in less computational time. Furthermore, in this work, we use an iterative MIP-based algorithm that guarantees that the network improves in each iteration instead of a genetic algorithm based approach. The iterative solution algorithm is easier to understand and needs less computational time. Finally, in this work, we analyze the effect of adding a large non-hub port to the main network, but we do not include it in the solution algorithm, because the cost reductions are only marginal, while Mulder and Dekker (2014) include different methods to add smaller ports to the main route network to their solution approach in order to improve the network profit.

Xia et al. (2015) study the joint fleet deployment, speed optimization and cargo routing problem. The authors incorporate a new fuel consumption function based on both speed and load of the ships. The problem is solved by clustering ports into a few large regions and construct routes between the regions. The authors do not consider the routes to the individual ports within each region.

A lot of research has been performed on network design in traditional liner shipping networks (for reviews on these works, see e.g. Ronen 1983, 1993, Christiansen et al. 2004, Meng et al. 2014). Brouer et al. (2014a) provide a benchmark model and data set based on real data from Maersk Line, which makes it possible to compare networks. The current best results for this benchmark data for Europe-Asia instances are found using the method of Brouer et al. (2014b). In this paper, we will use the Europe-Asia data from this benchmark paper and compare our results to the results of Brouer et al. (2014b) of which some corrections are reported in Brouer (2015).

In this paper we will investigate the profitability of making fewer port calls in two ways. First we will describe the considered problem in Section 2. In this section, we will also discuss the influence of making fewer port calls per route on different aspects that cannot always easily be captured in a mathematical model. Next, Section 3 describes the methods used to design a hub-and-feeder network. In Section 4, we conduct a case study for the Asia-Europe trade lane by applying the optimization methods of Section 3 on top of a pre-specified hub-and-feeder system, using demand data published by Brouer et al. (2014a). Next, Section 5 provides a improvement heuristic that adds an additional port to a route, whereafter conclusions are drawn in Section 6.

2 Problem description

In this paper we will focus on designing networks with a special structure. Our networks will be similar to so-called hub-and-feeder networks in which first a route network is constructed between a few large hub ports. Thereafter, all other ports are allocated to one of the hub port and for each hub port a regional network (also called feeder network) is constructed calling at the allocated hub ports. The hub-and-feeder structure of the considered networks is inspired by the big container ships that are used these days. These big ships are expected to be most profitable when large call sizes are realised during port calls, because port visits are expensive and calls with large call sizes will probably be more efficient than small calls. Ideally, big ships will

be as full as possible during the complete route and provide (approximately) direct connections between multiple ports. A hub route network with a limited number of hubs are likely to satisfy these conditions, because the total regional demand will be transported between the different hubs.
The problem studied in this paper can now be described as follows. Consider a given set of demands between origin and destination ports (also referred to as OD-pairs) and a set of available ships. The goal is to design a liner shipping network that can be used to transport the demand from the origin to the destination ports. The network will consist of a set of routes that will be sailed. Each route specifies which ports will be called at the route and in which order. A ship type has to be allocated to each route in such a way that each port on the route is visited an integer number of times each week. Clearly, only available ships can be used to allocate to routes. Furthermore, the sailing speed for each ship needs to be decided upon and should be in between the minimum and maximum allowed sailing speed of the allocated ship. Finally, the exact routing of cargo over the routes in the network needs to be determined. transshipments might be used in order to satisfy a demand against a given cost. The liner company receives a revenue for each container transported, but also incurs loading and unloading cost of the container. The company is allowed to reject containers against a given cost, denoting the loss of goodwill.

2.1 Analysis of influence of fewer port calls

A hub-and-feeder network will differ from traditional liner shipping networks in multiple aspects. An important difference is that traditional networks have more port calls per route than the networks that we will generate in this research. In this section, we will describe the influence of fewer port visits on the demand structure, transit time, (dis)economies of scale, uncertainty in port time, CO_2 emission, cost allocation and flexibility and competition.

2.1.1 Demand structure

Reducing the number of port calls per route will result in large fast container flows between the hubs. In this paper we assume that all demand has to be transported from its given origin to the given destination port. However, when for example Rotterdam will become a hub port with non-stop connections to Asia, it is inevitable that the demand at ports close to Rotterdam, like Antwerp and Hamburg, will (partly) shift towards Rotterdam. Containers can be transported by truck, train or barge from Rotterdam to Antwerp and Hamburg or directly to the real destination of the container. In general, a demand shift towards the hub ports is to be expected, because hub ports offer fast and frequent connections to other hub ports. Hinterland connections will be used to deliver containers at the hub ports, increasing the demand at hubs. This results in less transshipments in the networks, which is beneficial for the hub networks. Hence, the hub networks might perform better than indicated by the results in this paper, where we did not consider the demand change.

2.1.2 Transit time

The influence of introducing a hub-and-feeder network on transit time is considered by distinguishing between two different types of demand pairs: pairs of which both ports are hub ports in their region and pairs of which at least one port is a regional port.

Hub services provide more efficient transport between hub ports than traditional liner network, because fewer port stops per route are made. This will probably decrease the transit time for cargo demand between two hub ports. However, the second category is more difficult to evaluate. In the hub-and-feeder network, many of these demand pairs will need at least one transshipment, because at least one of the ports is not a hub. Assuming weekly port calls in liner shipping networks, the containers may have to wait up to one week for the connecting ship. In traditional liner shipping networks, the ports might be called at the same route, in which case no transshipment is needed. However, also in traditional networks, transshipments are likely, especially for small ports that are usually only visited at a few routes in the network. Furthermore, a connection between two ports on the same route is probably more efficient in hub-and-feeder networks than in traditional networks because of the reduction in port calls. With fewer port calls, the total distance of a route will probably decrease because ships need to sail less additional distance in order to make port calls. Furthermore, the route time decreases, because fewer port visits also means less port time. Hub networks consist of only a few ports, so the same port combination might be visited on multiple routes, increasing the frequency between hubs. Therefore, the additional time required for additional port calls on traditional routes and consequently the additional distance to be sailed can easily become larger than the transshipment time needed in a hub-and-feeder service. A disadvantage of hub-and-feeder networks is that regional origin (respectively destination) ports might be located closer to the destination (respectively origin) port than the hub port where the cargo has to be transshipped, so some backtracking has to occur. In this case, the distance between the origin (respectively destination) port and the hub has to be sailed twice. This disadvantage can partly be accounted for in the clustering algorithm, where this additional distance can be incorporated in the decision to allocate the regional port to a hub port.

In conclusion, the effect of a hub-and-feeder network on the transit time is not necessarily negative, but more research has to be done to draw exact conclusions. Transit time can be incorporated in the network design problem, but will increase the complexity of the problem even more, since trade-offs need to be made between costs and transit time. Therefore, we decided not to include the transit time as decision variables in our problem.

2.1.3 Economies of scale

Third, (dis)economies of scale influences the profitability of networks. Larger ships are well-known to be more efficient at sea, but they might be less efficient in ports (see for example Cullinane and Khanna 1999). However, in this research we investigate the reduction in port calls per route using the same ship types as are currently used by liner companies. The advantage of making fewer port stops compared to services calling at multiple ports is that more containers on the ship have to be unloaded during a port call. This reduces the complicated problem of container placement on ships and decreases the probability that containers are blocking other containers. However, the disadvantage of having fewer port calls is that more containers have to be loaded and unloaded during a port call, which might influence the port time. In the case study, we do not incorporate this aspect; all port calls take the same amount of time consistent with the approach in Brouer et al. (2014a). Furthermore, high container volumes are transported over a hub service. The high volumes justify the use of even larger container ships on hub services. In this way, shipping lines can benefit even more from economies of scale.

2.1.4 Uncertainty in port time

The next aspect we will consider is the uncertainty in port time. Port time uncertainties can arise from many different factors such as port/terminal congestion, unexpected waiting times before berthing or before starting loading/discharging and port/terminal productivity below expectation (Notteboom 2006). The probability of obtaining one of these delays increases when ships arrive delayed in a port, thereby missing their allocated time slots. Delay management is a very important issue in liner shipping. Shipping lines face high operational costs per day, so delays can be very costly (Vernimmen et al. 2007). Furthermore, shippers are faced with the possibility of losing customers. Therefore, shipping lines will try to maximize their schedule reliability. Ships sailing on services with fewer port calls will spend relatively more time at sea. Fewer port calls will clearly lead to a lower probability of incurring delays in ports. Furthermore, average sailing distances per sea leg increase when fewer ports are called per route, which gives rise to the possibility of recovering earlier obtained delays by increasing the sailing speed. Clearly, delays can always be recovered (at least partially) by increasing the sailing speed, but larger sailing distances imply smaller speed increases to capture the same amount of delay. Since daily bunker costs are usually assumed to be proportional to the third power of the sailing speed (Stopford 2009), larger increases in sailing speed can have disastrous

consequences on the bunker costs. Hence, services with fewer port calls are likely to recover from incurred delays in a less costly manner compared to other liner services, resulting in more timely port arrivals and thus lower probabilities of incurring port delays. Another factor influencing the port time uncertainty is the variation in call size. A hub service will typically be used to transport the cargo demand from one region to another region. Individual port demand is thus aggregated to port region demand, which will in general also increase the call size uncertainty. However, this effect is compensated by the decrease in number of port calls on the service. Which of these two effects will dominate the other depends on multiple factors, like correlation between call sizes.
Concluding, in general hub services might be able to decrease the port time uncertainty, because on-time arrivals can better be managed. However, uncertainty in call size can endanger the port time reliability.

2.1.5 CO_2 emissions

Next, we will consider the difference in CO_2 emissions between transport using hub services and transport using traditional liner services. Again, the total effect is difficult to estimate beforehand and depends on the exact network structure. On one hand, more transshipment movements are needed to transport the cargo from the origin to the destination port using hub-and-feeder networks, adding more CO_2 emissions to the process. On the other hand, hub services are more efficient at sea, decreasing the total CO_2 emissions. Therefore, no exact conclusions can be drawn with respect to the influence of hub-and-feeder networks on the CO_2 emissions. The amount of CO_2 emissions for a given route will be proportional to the bunker consumption at the route. Hence, after obtaining different networks, the amount of CO_2 emissions can easily be compared to each other. However, it is much more difficult to incorporate the amount of emissions in the optimization model, since trade-offs between total network costs and emissions have to be made.

2.1.6 Cost allocation

Liner companies are using shipping networks to provide connections between ports to deliver demand. The total network performance can easily be determined by determining the total costs and revenues of the network. In practice liner companies are often also interested in the cost or benefit of a single OD-pair. However, these costs are much more difficult to estimate, because multiple OD-pairs share connections and it is not obvious which part of the costs should be allocated to which OD-pair. This problem is referred to as the cost allocation problem. In traditional networks, this is a very difficult problem, because OD-pairs can usually be serviced using multiple different connections, which makes it unclear which OD-pairs should contribute to the costs of an individual route. Cost allocation will become more straightforward when using hub-and-feeder networks, because there will be fewer connections between OD-pairs. The extreme case in which the hub route consists of a non-stop connection between two ports, will clearly reveal the exact route of an OD-cargo.

2.1.7 Flexibility and competition

Finally, we compare the flexibility and competition potentials between hub-and-feeder and traditional liner shipping networks. Clearly, flexibility increases when more ports are visited on a route. Since the distance between two consecutive ports is usually smaller on routes with more port calls, ships have more opportunity to for example swap port calls if no berth is available in one of the ports at the expected arrival time. Furthermore, more port calls in a region might allow transport providers to change the origin port in case they are going to miss their connection, which also increases the potential for competition between ports. If only one port is visited in each region, the competitive position of all other (smaller) ports will weaken strongly. Hence, traditional networks provide both more flexibility and more competition potentials.

3 Solution methodology

This section discusses the hub-and-feeder network design problem. The goal is to construct a network satisfying the hub-and-feeder design. We propose an iterative solution algorithm in which the hub and feeder routes are iteratively updated given that the other routes are fixed. Algorithm 1 gives a description of the iterative solution approach. We first need to select the potential hub ports from the data. Then, given this set of hubs, clusters need to be designed. This is done in Step 1 of the algorithm using Algorithm 2, which will be described in Section 3.1. Next, we want to construct a route network consisting of hub and feeder or regional routes. Each route is denoted by a string of ports. The order of the ports denote the order in which they are visited on the route. Ports can be visited multiple times on a route. We require a weekly frequency of each route in the network. The hub and feeder subnetworks can be generated separately from each other. That is, given a set of feeder routes, the connecting hub routes can be optimized, while the optimal regional routes can be found given a realization of the satisfied demand obtained with fixed hub routes. Sections 3.2 and 3.3 describe respectively the network design of the hub and regional route networks.

The initial hub network in Step 2 is constructed as will be described in Section 3.2. Then, the initial regional route network can be constructed by solving the regional route network design (RRND) problem that will be introduced in Section 3.3 with as initial demand the real demand between each OD-pair. That is, in the construction of the initial regional route network, we assume that all demand should be satisfied. Furthermore, each cluster is allowed to use all available ships in the dataset. After constructing the initial hub and regional route network, the ship allocation and cargo routing (SACR) problem that will be described in Section 3.4 can be solved with a time limit. In this problem, ships are allocated to the routes in the network and the cargo allocation over the network is determined in order to determine the profitability of the network. Next, the demand satisfied in the network can be used as a new input in the regional route network design problem. Now, also more information about the availability of ships is known. For each cluster, the ships allocated to this cluster in the solution of the SACR problem will be available to use in the MIP formulation of the considered cluster. Furthermore, each ship that is not used in the SACR will be initially available in the RRND problem. After solving each MIP, these available ships will be updated: if one of the ships that was not used in the SACR is now allocated to a regional route, it is removed from the available ships, while ships that were initially allocated to a regional route, but are not allocated in the new optimal solution, are added to the available ships. In this way, a new regional route network is found and can be used to resolve the SACR problem. This can be repeated until no improvement is found. Note that in

Algorithm 1: Iterative algorithm

1. Run Algorithm 2 from Section 3.1 to obtain hubs and clusters.
2. Design hub network as described in Section 3.2.
3. Repeat as long as an improvement is found
   (a) Design regional route network as described in Section 3.3.
   (b) Solve ship allocation and cargo routing problem as described in Section 3.4 to determine new hub network and satisfied demand realization.

each iteration, the new regional route network will perform at least as good as the previous regional route network, because the previous network is always a feasible solution to the RRND problem. Hence, by using a MIP start for the SACR problem, with the ship allocation to the hub routes as in the previous solution to the SACR problem and the ship allocation to the regional routes as in the new optimal solution of the RRND problem, we are guaranteed to find a solution with a profit that is at least as high as the profit in the previous iteration.

The ship allocation and cargo routing problem is a well-known problem in liner shipping. Formulations used in existing literature to solve this problem, can be distinguished in two groups: flow-based formulations and path-based formulations. In general, path-based formulations outperform the flow-based formulations for small instances. However, the number of variables in path-based formulations will grow exponentially in the input size, while this growth is linear for flow-based formulations. Path-based formulations are often solved using column generation techniques. However, the number of variables in our instances are small enough to be able to generate all variables beforehand. Since it still becomes more difficult to find good solutions for instances with more than five hubs, we propose a new type of formulation: we combine the flow-based and path-based formulations in order to benefit from the advantages of both formulations. Section 3.4 will describe both the path-based formulation and this new formulation. In the case study, the performance of these formulations are compared and the best formulation is used in the iterative algorithm.

3.1 Hub selection and clustering

The clustering process is done in two parts: first hubs are determined with initial clusters, which are partitioned in smaller clusters in the second part. Algorithm 2 describes the clustering process. The first step uses a variant of the k-centroid clustering algorithm to find the initial clusters and corresponding hubs. These hubs are the potential hubs in our solution algorithm. In the k-centroid clustering algorithm, one starts with k initial ports that are used as hub ports. Then, each port is allocated to the closest hub port using a distance function. After the allocation, the distance function is used to determine the average distance of each port in a cluster to all other ports in this cluster. The port with the smallest average distance is chosen and used as new hub. Then the allocation and hub determination steps are repeated until the clusters are converged. Instead of the distance between two ports, we will use a different distance function in the k-centroid clustering algorithm. Since all cargo, except the cargo to and from a hub, has to be transshipped, it is preferred that hub ports are ports with large demand, because this will reduce the transshipment cost for the cluster. Furthermore, the location of the hub in the cluster is important, because all other ports are visited from the hub port. Therefore, we define the following distance function Δ^c_{ph} for $p \in \mathcal{P}$ and $h \in \mathcal{H}$:

$$\Delta^c_{ph} = \Delta_{ph} c^{nm} \left(\sum_{p' \in \mathcal{P}} (d_{pp'} + d_{p'p}) + \sum_{p' \in \mathcal{P}} \left(I_{\Delta_{pp'} \geq \Delta_{hp'}} d_{pp'} + I_{\Delta_{p'p} \geq \Delta_{p'h}} d_{p'p} \right) \right) + \sum_{od \in \mathcal{D}} d_{od} c^t_h I^t_{odh}. \quad (1)$$

In (1) $\mathcal{P}$, $\mathcal{H}$ and $\mathcal{D}$ are the set of ports, hubs and OD-pairs respectively, Δ_{ij} and d_{ij} are respectively the distance and demand between ports i and j and c^{nm} and c^t_i are respectively the average cost of transporting one container per nautical mile and the transshipment cost of port i. Furthermore, I_a returns 1 if statement a is true and 0 otherwise, while I^t_{odh} equals 1 if OD-pair od needs a transshipment at hub h and 0 otherwise. The distance used for the clustering algorithm Δ^c includes the cost of transshipping at the hub and the sailing cost from the hub port to the regional port. If the hub port is located further away from the destination (respectively origin) port than the origin (respectively destination) port, the sailing distance between the hub and the regional port is added twice in order to reduce the additional distances travelled by containers because of transshipments at hubs. The average sailing cost per container per nautical mile is estimated by taking an average over all ship types assuming that they will sail at design speed. Finally, we do not allow to sail through the Suez Canal in regional routes, since costs are associated to each passage of the Suez Canal.

Tighter draft restrictions lead to less ship types that are able to berth in that port. Since, larger ships usually have larger drafts, tighter draft restrictions prevent larger ships from being able to berth. Hence, ports with high demand in which large container ships are able to berth are most likely not visited on the same route as ports with only little demand or with limited draft restrictions. Hence, we do not want to allocate these ports to the same cluster. Thereto, Step 2 splits the ports in each cluster into large, medium and small ports based on draft limit and total port demand (sum of demand and supply in the data set). The current cluster is replaced by three groups each containing one of these groups of ports. The sets $\mathcal{P}^s$, $\mathcal{P}^m$ and $\mathcal{P}^l$ denote the sets with small, medium and large ports respectively. In the algorithm δ_i denotes the draft of port i and $\underline{\delta}$, $\bar{\delta}$, $\underline{d}$ and $\bar{d}$ are lower and upper bounds on the draft and port demand. Figure 1 shows an example of this step of the clustering algorithm.

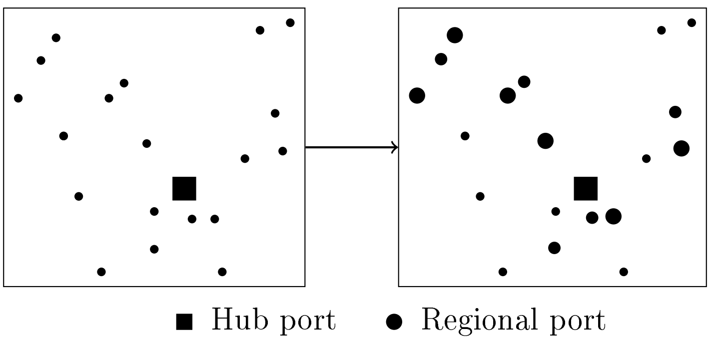

Figure 1: Example of Step 2 of Algorithm 2. The left part shows a hub port together with the allocated regional ports. In the right part, the regional ports are divided in small, medium and large regional ports.

A limit m on the total number of ports in a cluster is imposed. In Step 3 of the algorithm, clusters are split into two new clusters as long as the number of ports exceeds this limit. Splitting is based on a 2-centroid clustering algorithm. First, the two ports that are located most far apart from each other are used to initialize the two cluster centers. Ports are allocated to the closest cluster and the port that is most close to the geographical cluster center is used as new center. Then, clusters are updated using the same procedure, until they do not change any more or a predetermined number of updates have been performed. Figure 2 shows an example of Step 3 of the algorithm.

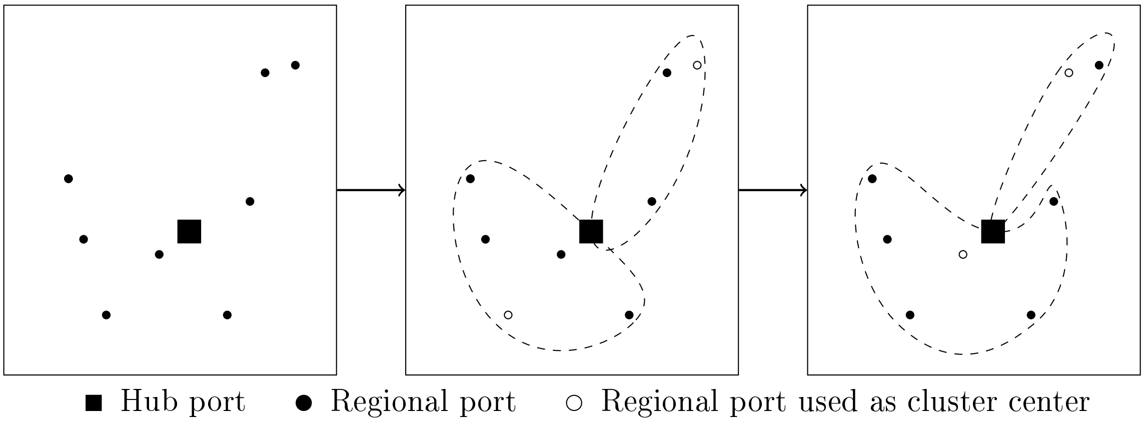

Figure 2: Example of Step 3 of Algorithm 2. The left part shows a hub port together with the allocated small, medium or large regional ports. In the middle part, the two regional ports that are located most far apart are used as cluster centers and all other regional ports are allocated to the closest cluster center. The right part shows the updated cluster centers and the new clusters.

Finally, some empty clusters might exist after the first steps of the algorithm, so Step 4 removes these empty clusters if they exist.

3.2 Hub network

The hubs are sorted based on geographical location starting in the far East and ending in Northern Europe. Then, hub routes are generated by complete enumeration of all routes that visit the hubs in geographical order. Hence, routes can visit a hub on the eastbound voyage, on the westbound voyage, on both the eastbound and the westbound voyage or on neither of the two voyages.

3.3 Regional network

In this section we will discuss the regional route network design problem. The clusters will be used in the generation of the regional route network. Only ports that belong to the same cluster might be visited on the same route. Hence, the regional route network design problem can be split into a separate problem for each cluster. Furthermore, we assume that all regional ports will be visited on at most one route. Since almost no regional demand is included in the dataset, almost the total supply

Algorithm 2: Clustering algorithm

1. Initialize clusters and determine hubs using a k-centroid clustering algorithm with distance function Δ^c as defined in (1) and using the k largest ports as initial hubs.

2. For each hub, split the cluster into three new clusters with small, medium and large ports respectively:

   - $\mathcal{P}^s = \left\{ p \in \mathcal{P} : \sum_{p' \in \mathcal{P}} (d_{pp'} + d_{p'p}) \leq 2\underline{d} \frac{\sum_{od \in \mathcal{D}} d_{od}}{|\mathcal{P}|} \vee \delta_p \leq \underline{\delta} \right\}.$
   - $\mathcal{P}^m = \left\{ p \in \mathcal{P} : p \notin \mathcal{P}^s \wedge \left(\sum_{p' \in \mathcal{P}} (d_{pp'} + d_{p'p}) \leq 2\bar{d} \frac{\sum_{od \in \mathcal{D}} d_{od}}{|\mathcal{P}|} \vee \delta_p \leq \bar{\delta} \right) \right\}.$
   - $\mathcal{P}^l = \{ p \in \mathcal{P} : p \notin \mathcal{P}^s \cup \mathcal{P}^m \}.$

3. As long as $\exists i : |\{p \in \mathcal{P} : p \in C_i\}| \geq m$, repeat for these clusters:

   - Split the cluster in two new clusters using the 2-centroid clustering algorithm with distance function Δ and initial centers the two ports that are located most far apart.

4. Remove all empty clusters if applicable.

and demand of a port, will be delivered to and from the hub respectively. Hence, the regional network design problem is very similar to a vehicle routing problem with simultaneous pickups and deliveries and a heterogeneous fleet. The maximum number of ports in a cluster will be chosen in such a way that all routes starting and ending at the hub can be generated and included in a mixed integer programming (MIP) model. For each route, the port on the route with the smallest draft restricts which ship types can be used for this route. Hence, the feasible ship types for each route can be calculate beforehand and is input for the MIP model.

We introduce the following notation in order to define the RRND model.

$\mathcal{P}^c$	set of ports in the considered cluster (except the hub port).
$\mathcal{R}$	set of routes.
$\mathcal{R}_p$	set of routes containing port $p \in \mathcal{P}^c$.
$\mathcal{S}^c$	set of available ships for the considered cluster.
$\mathcal{V}_{rs}$	set of speeds that ship $s \in \mathcal{S}^c$ can sail at route $r \in \mathcal{R}$ to obtain a weekly duration.
c^r_{rsv}	weekly route cost of sailing route $r \in \mathcal{R}$ per ship of type $s \in \mathcal{S}^c$ with speed $v \in \mathcal{V}_{rs}$.
t_{rsv}	duration of route $r \in \mathcal{R}$ if ship type $s \in \mathcal{S}^c$ is used at speed $v \in \mathcal{V}_{rs}$.
$\tilde{c}^t_r$	transshipment cost of route $r \in \mathcal{R}$ for satisfying demand between two ports that are allocated to the same cluster.
n_s	number of available ships of type $s \in \mathcal{S}^c$.
q_{prsv}	fraction of demand of port $p \in \mathcal{P}^c$ satisfied when route $r \in \mathcal{R}$ is sailed once a week with ship type $s \in \mathcal{S}^c$ and speed $v \in \mathcal{V}_{rs}$.
y_{rsv}	number of weekly port calls on route $r \in \mathcal{R}$ using ship type $s \in \mathcal{S}^c$ with speed $v \in \mathcal{V}_{rs}$.
z_r	binary variable indicating whether route $r \in \mathcal{R}$ is used or not
k	constant equal to the number of available ships.

Note that t_{rsv} not only denotes the duration of a route, but also the number of ships that need to be allocated to the route in order to obtain a weekly frequency. The mixed integer programming formulation is given by:

$$\min \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}^c} \sum_{v\in\mathcal{V}_{rs}} c^r_{rsv} t_{rsv} y_{rsv} + \sum_{r\in\mathcal{R}} \tilde{c}^t_r z_r \tag{2}$$

$$\text{s.t.} \quad \sum_{s\in\mathcal{S}^c} \sum_{v\in\mathcal{V}_{rs}} \frac{1}{k} y_{rsv} \leq z_r \qquad r \in \mathcal{R} \tag{3}$$

$$\sum_{r\in\mathcal{R}_p} \sum_{s\in\mathcal{S}^c} \sum_{v\in\mathcal{V}_{rs}} q_{prsv} y_{rsv} \geq 1 \qquad p \in \mathcal{P}^c \tag{4}$$

$$\sum_{r\in\mathcal{R}_p} z_r = 1 \qquad p \in \mathcal{P}^c \tag{5}$$

$$\sum_{r\in\mathcal{R}} \sum_{v\in\mathcal{V}_{rs}} t_{rsv} y_{rsv} \leq n_s \qquad s \in \mathcal{S}^c \tag{6}$$

$$y_{rsv} \in \mathbb{Z} \qquad r \in \mathcal{R} \quad s \in \mathcal{S}^c \quad v \in \mathcal{V}_{rs} \tag{7}$$

$$z_r \in \{0,1\} \qquad r \in \mathcal{R}. \tag{8}$$

The objective is to minimize the total costs associated with the selected routes. Since all demand has to be satisfied, (un)loading costs will be constant and do not need to be included in the total costs. Also most transshipment costs will be incurred in every feasible route network. For example, if the closest hub to the origin port of a demand pair is different from the closest hub to the destination port of this demand pair, the transshipment cost at the hubs will always be incurred. Furthermore, if the hubs are the same, but the origin and destination port are allocated to different clusters, the demand is also always transshipped at the hub, because the route networks are solved per cluster. So, the only transshipments that might or might not be included in the total costs are transshipments of demand pairs with the origin and destination both allocated to the same cluster. Therefore, these are the only transshipment costs included in the objective. In order to include these transshipment cost exactly once per container, the transshipment costs are only included in $\tilde{c}_r^t$ if the origin and destination port of the demand pair are both allocated to the same cluster and the origin port is part of route $r \in \mathcal{R}$, while the destination port is not. Finally, the first part of the objective gives the total route costs of the selected routes. In the route cost c_{rsv}^r, the weekly fixed cost of ship type $s \in \mathcal{S}^c$, the weekly port call costs and the weekly fuel cost (both fuel cost on sea as during port stays) of sailing route $r \in \mathcal{R}$ with ship type $s \in \mathcal{S}^c$ at speed $v \in \mathcal{V}_{rs}$ are included. Hence,

$$c_{rsv}^r = 7c_s^f + \frac{e\tilde{f}_s \left(\frac{v}{\tilde{v}_s}\right)^3 t_{rsv}^s + e\tilde{f}_s^p t_r^p + \sum_{p \in \mathcal{R}_p} c_{ps}^p}{t_{rsv}},$$

where c_s^f is the daily fixed cost of ship type $s \in \mathcal{S}^c$, e is the bunker price in USD per ton, $\tilde{f}_s$ and $\tilde{f}_s^p$ are the fuel consumption in ton per day for ship type $s \in \mathcal{S}^c$ when sailing at design speed and when berthing in a port respectively. Further, $\tilde{v}_s$ is the design speed in knots of ship type $s \in \mathcal{S}^c$ and t_r^p and t_{rsv}^s are respectively the port and sailing times in days of sailing route $r \in \mathcal{R}$ with ship type $s \in \mathcal{S}^c$ at speed $v \in \mathcal{V}_{rs}$. The cost of calling at port $p \in \mathcal{P}^c$ with ship type $s \in \mathcal{S}^c$ is denoted by c_{ps}^p. Finally, routes are generated such that

$$t_{rsv} = \frac{t_r^p + t_{rsv}^s}{7} \in \mathbb{N}.$$

Constraints (3) guarantee that z_r will take value 1 if route $r \in \mathcal{R}$ is used by some ship type. Constraints (4) ensure that all demand is satisfied, while Constraints (5) make sure that each port is visited on exactly one route. The limited availability of ships is imposed by Constraints (6). Finally, Constraints (7) and (8) ensure the integrality and binary conditions on the decision variables.
After solving the MIP model (2)-(8) for each cluster, the routes that are used in the optimal solutions are added to the regional network.

3.4 Ship allocation and cargo routing

The hub network and regional network form together the input network for the ship allocation and cargo routing problem. Note that the regional network already consists of routes visiting each regional port exactly once, such that only the ship allocation to these routes still has to be solved (unless some ports will not be visited at all in the network). The hub network, on the other hand, consists of all possible routes visiting only (some of) the hub ports, so we still need to decide which routes will be used. The ship allocation and cargo routing problem can also be modelled using a MIP formulation. Thereto, we first introduce some additional notation:

$\mathcal{L}$	set of legs.
$\mathcal{D}$	set of origin-destination demand pairs (OD-pairs).
$\mathcal{Q}$	set of paths.
$\mathcal{Q}_l$	set of paths containing leg $l \in \mathcal{L}$.
$\mathcal{Q}_{od}$	set of paths satisfying demand $od \in \mathcal{D}$.
$\mathcal{R}_l$	set of routes containing leg $l \in \mathcal{L}$.
c_{od}^{ls}	cost per TEU of not satisfying demand $od \in \mathcal{D}$.
c_q^q	cost of transporting one TEU over path $q \in \mathcal{Q}$.
b_s	capacity in TEU of ship type $s \in \mathcal{S}$.
d_{od}	demand of OD pair $od \in \mathcal{D}$.
x_q	amount in TEU transported over path $q \in \mathcal{Q}$.
L_{od}	amount in TEU of unsatisfied demand between $od \in \mathcal{D}$.

Note that a path consists of a certain number of legs, so for example $q_1 = (l_1, l_2, l_3)$ denotes a path containing three legs. Each leg consists of two consecutive ports visited on a route together with the route they are visited on, for example $l_1 = (p_1, p_2, r_1)$ denotes the leg between ports p_1 and p_2 visited consecutively on route r_1. The costs of a path are defined as the sum of the loading, unloading and possible transshipment costs minus the revenue of satisfying the demand of the OD-pair. Each OD-pair has one or multiple paths associated to it (the paths that start at the origin and end at the desination port of the OD-pair). The structure of the input network guarantees that the number of paths per OD-pair is limited: the subpath from the origin port to the first hub port (only applicable if the origin port is not a hub) is unique, because every regional port is on exactly one regional route. Similarly, the subpath from the last hub port to the destination (if applicable) is unique. Hence, the number of different OD-paths is equal to the number of different subpaths between the two hubs, which results in a limited number of total paths. This is important because in general the number of paths in a network can grow very fast. Since each path is associated with a variable in the mixed integer programming formulation, this would most likely result in too many variables, such that more advanced techniques, like column generation, are needed to solve the MIP. However, the special structure of our input network guarantees that it is possible to include all variables in the formulation without the necessity of using additional techniques. The mixed integer programming formulation is given by:

$$\min \sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{v\in\mathcal{V}_{rs}} c^{r}_{rsv} t_{rsv} y_{rsv} + \sum_{od\in\mathcal{D}} c^{ls}_{od} L_{od} + \sum_{q\in\mathcal{Q}} c^{q}_{q} x_q \tag{9}$$

$$\sum_{q\in\mathcal{Q}_{od}} x_q + L_{od} = d_{od} \qquad od \in \mathcal{D} \tag{10}$$

$$\sum_{q\in\mathcal{Q}_l} x_q \leq \sum_{r\in\mathcal{R}_l}\sum_{s\in\mathcal{S}}\sum_{v\in\mathcal{V}_{rs}} b_s y_{rsv} \qquad l \in \mathcal{L} \tag{11}$$

$$\sum_{r\in\mathcal{R}}\sum_{v\in\mathcal{V}_{rs}} t_{rsv} y_{rsv} \leq n_s \qquad s \in \mathcal{S} \tag{12}$$

$$x_q \geq 0 \qquad q \in \mathcal{Q} \tag{13}$$

$$y_{rsv} \in \mathbb{Z} \qquad r \in \mathcal{R} \;\; s \in \mathcal{S} \; v \in \mathcal{V}_{rs}. \tag{14}$$

The objective of the model is to minimize the total cost minus the revenue. Note that negative objective values correspond to positive profits and hence, we are actually maximizing total profit. The revenue is included in the costs of the paths. The total costs consists of (un)loading and transshipment costs (included in the path costs), penalties associated to lost sales and total route costs (fixed ship costs, port call costs and fuel costs during sailing and berthing in ports). Constraints (10) ensure that all demand is either satisfied using one of the OD-paths or lost. Further, Constraints (11) denote the capacity constraints on each of the legs in the network. The limited availability of ships is modelled in the same way as in the regional route network design problem by Constraints (12). Finally, Constraints (13) and (14) ensure the nonnegativity and integrality of the path flows and number of allocated ships respectively.

3.4.1 Reducing the number of variables

Although the total number of paths is small enough to be included in the MIP formulation, we can improve upon the formulation by using a modelling trick. As already explained above, the start and end subpath of each OD-pair is unique. By introducing an artificial leg between the two hub ports, we can reduce the number of paths to one for each OD-pair. Hence, each path consists of the unique start subpath, the artificial leg between the two hubs and the unique end subpath. This reduces the number of paths and thus the number of variables even further. However, additional constraints are needed to ensure that the flow over the artificial leg is sent over existing legs in the network. Thereto, we introduce:

$\mathcal{L}'$ set of artificial legs added to the network.

$\mathcal{Q}'_{l'}$ set of paths in the network that can be used to transport flow over artificial leg $l' \in \mathcal{L}'$.

Furthermore, the set of paths in the new formulation will now consist of the unique OD-path for each OD-pair and all possible paths between two hubs in the network. Hence, if q is a unique OD-path, then $q \in \mathcal{Q}$ and if q is a path between two possible hubs, then $q \in \mathcal{Q}'_{l'}$ with l' denoting the two hubs that are the start and end ports of the path. The following constraints can now be added to the formulation (9)-(14):

$$\sum_{q \in \mathcal{Q}_{l'}} x_q = \sum_{q \in \mathcal{Q}'_{l'}} x_q \qquad l' \in \mathcal{L}'. \tag{15}$$

Constraints (15) ensure that all flow that is sent over an artificial leg is also allocated to one of the existing paths between the first and last port of the artificial leg. Hence, the constraints ensure that all flow is allocated over the real network. The resulting mixed integer program (9)-(15) has less variables and generates better solution in shorter computational times. Note that transshipment on hub routes can be handled by adding constraints of type (15) twice to the model. The first time, the flow balance between artificial legs in OD-paths and artificial legs in transshipment paths is modelled. The second time, they model the flow balance between the artificial transshipment legs and the real hub legs.

4 Case study

In this section, the results of the optimization methods applied to a case study on the Asia-Europe trade lane are discussed.

4.1 Data

We use the Asia-Europe data from LINERLIB (Brouer et al. 2014a), where also the low, base and high capacity scenarios are introduced. The data contains information on 114 ports on the Asia-Europe trade lane. Furthermore, demand for 4000 OD-pairs is given together with the availability and characteristics of six different ship types. The data contains some unlikely values for the transshipment cost. Some ports have transshipment cost of 0 or almost 0, which results in a large underestimation of the costs of these ports. Therefore, we decided to use the average transshipment costs for these ports, since this will advantage ports with large throughput to be selected as hub ports.

4.2 Hubs

The potential hubs are determined using the 7-centroid clustering algorithm with distance function as given in (1) and $c^{nm} = 0.075$. This results in the following seven potential hubs with their corresponding region: Bremerhaven (Northern Europe), Rotterdam (Northern Europe), Algeciras (Southern Europe), Jebel Ali (the Middle East), Tanjung Pelepas (the Singapore region), Shenzhen (Southern China) and Shanghai (the Far East). We will run several experiments including 2-7 of the above potential hub ports as hubs in the network. When including only 2, 3 or 4 hubs, we select respectively from the largest 4, 5 and 6 hubs (in total port demand).

4.3 Effect of reducing variables

In this section, we compare the mixed integer formulations (9)-(14) (SACR model) and (9)-(15) (reduced SACR model) for the SACR problem. To this purpose, we perform one step of the iterative algorithm for the base case for both formulations and compare the number of variables, best lower and upper bound and optimality gap. Tables 1 and 2 show the averages of these characteristics for all instances with 3, 4, 5, 6 and 7 hubs for the two formulations. We did not include instances with 2 hubs, since the formulations are the same for these instances. The tables clearly

#Hubs	#Variables	LB ($\times 10^6$ USD)	UB ($\times 10^6$ USD)	Gap (%)
3	16,989	541	646	23.08
4	55,204	541	772	48.78
5	219,348	97	895	3,754.44
6	900,238	−1,979	96,747	4,989.76
7	3,671,793	−1,979	2,713,284	137,234.30

Table 1: Characteristics for the SACR model

#Hubs	#Variables	LB ($\times 10^6$ USD)	UB ($\times 10^6$ USD)	Gap (%)
3	8,628	566	605	7.46
4	9,436	667	709	6.70
5	13,282	761	822	8.48
6	31,269	818	936	15.77
7	114,093	831	1,047	26.06

Table 2: Characteristics for the reduced SACR model

show that formulation (9)-(15) is better suitable for our solution algorithm than the formulation without Constraints (15): both the obtained solutions within the time limit and the upper bounds are better using this formulation. Furthermore, the reduced model is able to find feasible solutions for all number of hubs within the time limit, while the original model could not find any feasible solution for instances with six and seven hubs.

4.4 Results

Table 3 shows the profits of the route networks found using Algorithm 1 for low, base and high capacity scenarios with different potential hubs as input. The table only shows the combinations of potential hubs that resulted in the most profitable networks. The first column of Table 3 shows which potential hubs are included while running Algorithm 1: Bremerhaven (Br), Rotterdam (Ro), Algeciras (Al), Jebel Ali (JA), Tanjung Pelepas (TP), Shenzhen (She) and Shanghai (Sha). The second, third and last columns show respectively the profit in million USD of the network found for the low, base and high capacity scenarios. All instances are run with 10 and 12 meters as lower and upper draft bounds respectively. The lower and upper demand bounds are respectively given by 0.25 and 1.5. We allow for at most 6 ports and at most 10 changes per cluster. Finally, the running time of the ship allocation and cargo routing model is set to 180 sec.

	Profit in million USD		
Included hubs	Low	Base	High
Al, JA, TP, She, Sha	505.183	**966.284**	1,187.393
Ro, Al, JA, TP, She	535.303	928.968	1,148.290
Br, Al, JA, TP, She	528.651	933.594	1,171.080
Br, Ro, Al, JA, TP	493.625	916.989	1,174.196
Ro, Al, JA, TP, She, Sha	532.965	937.362	1,188.981
Br, Al, JA, TP, She, Sha	517.896	945.572	**1,194.305**
Br, Ro, Al, JA, TP, She	537.073	948.088	1,179.914
Br, Ro, Al, JA, TP, She, Sha	**539.501**	944.504	1,125.379
Current best network	373.000	758.549	937.461

Table 3: Profit for the low, base and high capacity scenarios

Table 3 shows the networks obtained for different configurations of hub ports. In general, the profit increases when a potential hub port is added. The best network with two hubs for the base instance has a profit of 806 million USD. This increases to almost 829, 876 and 966 million USD for networks with three, four and five hubs included. Remarkably, adding the sixth and seventh hub, decreases the profit of the found network. The last row of the table shows the profit of the current best network in literature for the low, base and high capacity scenarios of the Asia-Europe LINERLIB data (Brouer et al. 2014b, Brouer 2015). Our best networks provide an

increase in profit of 44.6%, 27.4% and 27.4% respectively for the low, base and high capacity scenario with respect to the current best networks in literature.
Table 4 shows some characteristics of the best route networks, i.e. the networks corresponding with the bold profits in Table 3. The first part of the table shows cost characteristics of the networks. Since vessels are more expensive in lower capacity scenarios, the fleet cost is decreasing when the capacity scenario increases from low to high. Furthermore, the lost sales cost also decreases, because more capacity results in more satisfied demand. The table also shows that the bunker costs are decreasing while the port costs are increasing when the capacity scenario increases from low to high. Hence, more direct routes are chosen when the vessel costs increases, leading to less port visits. The second part of the table shows some other characteristics of the networks. With less capacity, less ships are available which results in less routes. The hub routes have in general high utilization, resulting in high best peak and average utilization in all three capacity scenarios. Finally, the number of transshipments is relatively high in the network, because many OD-pairs need one or two transshipments in order to be satisfied.

	Low	Base	High
Revenue	3,354.258	3,471.728	3,592.852
Fleet cost	718.560	646.740	581.760
Bunker cost	687.669	487.571	459.203
Move cost	643.074	673.211	689.307
transshipment cost	221.302	238.466	228.645
Port cost	104.030	113.424	131.603
Canal fees	248.576	248.576	269.843
Lost sales cost	191.546	97.457	38.186
Profit	539.501	966.284	1,194.305
Fleet deployment	100.00	99.43	92.45
Nr routes used	57	64	71
Average port calls per week	2.04	1.76	1.77
Best peak utilization	100.00	100.00	100.00
Worst peak utilization	26.75	10.50	4.75
Best average utilization	97.83	97.06	99.83
Worst average utilization	14.29	8.13	4.73
Average nr transshipments	1.13	1.28	1.26
Percentage rejections	9.68	4.93	1.93

Table 4: Characteristics for the best networks with low, base and high capacity

5 Local improvement heuristic: adding a stop to a hub route

In this section, we propose a local improvement heuristic to improve the obtained networks. Thereto, we investigate whether it is profitable to add an additional port to a hub route. In this way we get more insight into the trade-offs. We take one of the hub routes used in the best network of the base case found when including Algeciras, Jebel Ali, Tanjung Pelepas, Shenzhen and Shanghai as hubs and show with some calculations whether it is profitable to also visit another port.
Given the route distance, the sailing time in days and speed in knots can be calculated by respectively:

$$t^s_{rsv} = 7t_{rsv} - t^p_r \tag{16}$$

and

$$v = \frac{\Delta_r}{24t^s_{rsv}} \tag{17}$$

where Δ_r is the route distance of route $r \in \mathcal{R}$ in nmi, t_{rsv} is the route time of sailing route $r \in \mathcal{R}$ with ship type $s \in \mathcal{S}$ at speed $v \in \mathcal{V}_{rs}$ in weeks and t^p_r is the total port time of route $r \in \mathcal{R}$ in days. Note that v should be in between a ship-dependent minimum speed v^{min} and maximum speed v^{max}. The bunker cost c^b_{rsv} of route $r \in \mathcal{R}$ sailed with ship type $s \in \mathcal{S}$ at speed $v \in \mathcal{V}_{rs}$ can be computed using the formula:

$$c^b_{rsv} = e\tilde{f}_s \left(\frac{v}{\tilde{v}_s}\right)^3 t^s_{rsv} + e\tilde{f}^p_s t^p_r, \tag{18}$$

where e is the bunker price in USD per ton, $\tilde{f}_s$ is the fuel consumption in ton per day at design speed of the vessel type $s \in \mathcal{S}$, $\tilde{v}_s$ is the design speed in nmi/hr of ship type $s \in \mathcal{S}$ and $\tilde{f}^p_s$ is the fuel consumption of the ship $s \in \mathcal{S}$ in ton per day when idling at a port.
Using (18) we can calculate the bunker cost for each route and hence the difference in the bunker cost after adding an additional stop. Furthermore, an additional stop results in additional port dues, which can be calculated by:

$$c^p_{ps} = f^p_p + v^p_p b_s, \tag{19}$$

where f^p_p is the fixed port call cost at port $p \in \mathcal{P}$ and v^p_p the variable port cost at port $p \in \mathcal{P}$ per FFE capacity of the ship berthing at the port. Finally, transshipment costs decrease by making an additional port call. The transshipment cost made to transship the containers at the nearest hub will be saved for the containers that can now directly be loaded or unloaded at the new port, which results in a savings on transshipment cost s_p^t at hub $h \in \mathcal{H}$ of.

$$s_p^t = nc_p^t, \tag{20}$$

where n denotes the number of FFE that can now directly be loaded or unloaded in the new port instead of needing a transshipment at the nearest hub and c_p^t denotes the transshipment cost per container at the nearest hub $h \in \mathcal{H}$.

We consider the hub route Shanghai - Algeciras - Shanghai. 8 post panamax ships with a capacity of 4,200 FFE are allocated to this route. Each ship needs 8 weeks to complete the route once, so that every week a port call is realized on this route. Since only two ports are called on the route, the total port time of the route equals two days. We will investigate whether it is profitable to make an additional stop in Rotterdam and Hong Kong, which are also ports with a relatively large demand. We assume that the port rotation time remains the same and accommodate the extra stop by changing the ship speed. Through this choice we make the comparison insightful, though also other options exist. Yet these may require a complete network change.

The current route distance is equal to 18,280 nautical miles (nmi). Using (17), we can now determine the sailing speed on the shuttle route. The sailing speed is equal to 14.1 nmi/hr. The design speed of a super panamax vessel is 16.5 nmi/hr, the bunker price is assumed to be 600 USD/ton, the fuel consumption at design speed is 82.2 ton/day and the fuel consumption when idling at a port equals 7.4 ton/day. The bunker costs can then be found using (18) and equal 1,672,594 USD.

The next sections describe the effect of additional port calls at Rotterdam and Hong Kong. An overview of the cost differences for these two ports can be found in Table 5.

5.1 Additional stop in Rotterdam

The route distance increases with 15.1% to 21,048 nmi when Rotterdam is added to the route. Furthermore, an additional port call results in an increase in port time from two to three days. The new speed that has to be sailed to complete the route in nine weeks can be determined using (16) and (17) and is equal to 16.5 nmi/hr. Using (18), we find that the new bunker cost are equal to 2,649,762 USD. Hence, making an additional port call at Rotterdam will lead to an increase in bunker costs of 977,169 USD. Furthermore, additional port costs are incurred by the additional stop in Rotterdam. The fixed port cost of Rotterdam is equal to 19,187 USD and the variable cost is 16 USD/FFE. The capacity of the ships is given above and is equal to 4,200 FFE, which results in an additional port cost of 86,387 USD by (19). The savings made by adding Rotterdam to the hub route depend on the number of FFE to be directly (un)loaded at Rotterdam instead of Algeciras. Containers originating at or destined for Rotterdam needed to be transshipped at the port of

Algeciras in the old scenario. The transshipment cost at Algeciras is 136 USD/FFE. In total, 2,520 FFE, which originate from or destine for Rotterdam, can be shipped by the considered hub service per week. The total savings can be found using (20) and are equal to 342,720 USD. Hence, adding Rotterdam to the hub route will result in additional costs of 720,836 USD and will thus not be profitable.

5.2 Additional stop in Hong Kong

Next, we will perform the analysis for the port of Hong Kong. Adding Hong Kong after Shanghai to the original hub route will result in a smaller detour than when adding Rotterdam. The total route distance will increase with 0.35% to 18,344 nmi. Using (16) and (17) we then find a new speed of 14.4 nmi/h. The bunker route costs can again be calculated using (18) and increase with an amount of 86,018 to 1,758,611 USD. The fixed port cost of Hong Kong is equal to 6,809 USD and the variable cost is 2 USD/FFE. Hence, we find additional port costs of 15,209 USD using (19). In total 4,051 FFE originating from or destined for Hong Kong are transported on the hub route per week. The transshipment cost of Shanghai is equal to 62 USD/FFE. Hence, by (20) a total saving in transshipment cost of 251,162 is found. In total, adding Hong Kong to the hub route will result in cost savings of 149,935 USD. Hence, adding Hong Kong to the hub route will be profitable.

	Rotterdam	Hong Kong
Difference in bunker cost	977,169	86,018
Difference in port call cost	86,387	15,209
Difference in transshipment cost	−342,720	−251,162
Total cost of additional stop	720,836	−149,935

Table 5: Cost differences in USD for additional stops in Rotterdam and Hong Kong

5.3 Conclusion

The above proposed procedure can be used as a local improvement heuristic to improve the networks found in Section 4. However, adding regional ports to hub routes destroys the nice structure we are exploiting in Section 3. In this section, we use the property that regional ports are only visited on one regional route to limit the number of paths needed in the mixed integer program to formulate the SACR problem. When we will start adding regional ports to hub routes, the number of paths will increase, especially when multiple regional ports are visited on hub routes. Hence, the complexity of the SACR model will increase, making it even harder to find good solutions. We have also seen in this section that it is not evident that adding a regional port to a hub route will result in a cost reduction. Furthermore, if we are able to find cost reductions, the improvements are only marginal. Therefore, we decide not to include the improvement heuristic in our solution algorithm.

6 Conclusion

Container ship sizes have increased during the last few years. Bigger ships might incur higher costs in ports; hence fewer port visits might increase the route efficiency. The goal of this research has been to investigate the profitability of a hub-and-feeder network with only a few port calls per route.

The influence of a hub-and-feeder network on the demand structure, transit time, (dis)economies of scale, port time uncertainty, delay management and flexibility and competition is discussed. Hub ports will in general attract more demand, because they offer fast and frequent services with other hub ports. Hence, a demand shift towards hub ports is to be expected when introducing hub-and-feeder services. Hence, the hub networks might even be more profitable than already indicated by the results in this paper. Hub-and-feeder networks will in general result in more transshipments, which can result in longer transit times. However, in hub-and-feeder systems, hub routes are relatively fast routes and are sailed frequently, which will probably balance the increase in time caused by the increase in transshipments. Furthermore, hub services benefit more from the economies of scale at sea than traditional liner routes, because the fraction of sailing time with respect to route duration is higher for hub services. Moreover, hub services will most likely justify the use of even larger container ships. The effect on port time uncertainty is more difficult to estimate, because on one hand on-time arrivals can better be managed for hub services, which significantly reduces the probability of incurring delays in ports. On the other hand, larger uncertainty in call size endangers the port time reliability. However, these possible delays are easier and most probably cheaper to manage for hub services, because ships have to cover large distances at each sea leg of a hub service. The increase in sailing speed needed to capture a certain amount of time is then smaller compared to shorter sea legs. Although all these studies have their limitations, they do give an indication that hub-and-feeder networks are an interesting and efficient concept, like they are in airlines.

An iterative solution approach is proposed to solve the problem. In the iterative approach, first the clusters corresponding to each hub are determined. Thereafter, all possible hub routes are generated. The initial regional route network can be generated under the assumption that all demand will be satisfied. Given a fixed regional route network, the ship allocation and cargo routing problem can be formulated and solved. However, since the problem has to be solved multiple times, we do not necessarily solve the problem to optimality, but impose a time limit. The solution to this problem results in a new realization of the satisfied demand, which can be used

to reoptimize the regional route network. The iterative solution approach repeats these steps until no improvement is found.
A new formulation is proposed to solve the ship allocation and cargo routing problem. This formulation basically combines ideas from the existing flow-based and path-based formulations. We compare our new formulation with a typical path-based formulation and conclude that the new formulation clearly outperforms the path-based formulation: both the found solution and the best bound obtained after a fixed time are better for the new formulation.
A case study is performed using the data benchmark set as introduced in Brouer et al. (2014a). In the case study, the profitability of route networks using combinations of seven potential hub ports (Bremerhaven, Rotterdam, Algeciras, Jebel Ali, Tanjung Pelepas, Shenzhen and Shanghai) is investigated using the iterative algorithm. Three scenarios with low, base and high capacity are considered. The results show that including all seven hubs results in the best network for the low capacity case, while for the high capacity case all hubs except for Rotterdam and in the base case all hubs except for Rotterdam and Bremerhaven should be included to obtain the best networks. Finally, the results show that our networks perform better than the reference network as discussed in Brouer et al. (2014b) and Brouer (2015) with profit increases of respectively 44.6%, 27.4% and 27.4% for the low, base and high capacity scenarios.
Next, an improvement heuristic is proposed in which the profitability of an additional port call at a hub service is investigated. In the example, the hub service between Shanghai and Algeciras is considered and the costs and savings of adding Rotterdam and Hong Kong respectively to the route are calculated. It is concluded that adding Hong Kong to the hub service is beneficial, while adding Rotterdam is not profitable. The profitability mainly depends on the additional distance that has to be covered, the number of FFE for which the number of transshipments can be reduced and the transshipment cost of the closest hub. However, the changes in profit are very small. Furthermore, adding ports to hub services will destroy the structure of the MIP models. Therefore, the improvement heuristic is not added to the solution algorithm.

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