Optimization in container liner shipping

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Econometric Institute Report 2016-05

Abstract

We will gives an overview of several decision problem encountered in liner shipping. We will cover problems on the strategic, tactical and operational planning levels as well as problems that can be considered at two planning levels simultaneously. Furthermore, we will shortly discuss some related problems in terminals, geographical bottlenecks for container ships and provide an overview of operations research methods used in liner shipping problems. Thereafter, the decision problems will be illustrated using a case study for six Indonesian ports.

1 Introduction

Seaborne shipping is the most important mode of transport in international trade. 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, because shipping is more cost efficient and environmentally friendly (Rodrigue et al. 2013). Reviews of maritime transport provided by the United Nations Conference on Trade And Development (UNCTAD 2014) show that about 80% of international trade is transported (at least partly) by sea. Sea transport can be separated into dry bulk (e.g. steel, coal and grain), liquid bulk (e.g. oil and gas) and containerized cargo. In 2013, containerized cargo is with a total of 1.5 billion tons responsible for over 15% of all seaborne trade, which resulted in a world container port throughput of more than 650 million twenty-foot equivalent units (TEUs).

The shipping market comprises three types of operations: tramp shipping, industrial shipping and liner shipping (Lawrence 1972). Tramp ships have no fixed route, but ensure an immediate delivery for any type of cargo from any port to any port, resulting in irregular activities. The behaviour of tramp ships is thus comparable to taxi services. In industrial shipping the cargo owner also controls the ships used to transport the freight. The objective of industrial operators is to minimize the cost of shipping the owned cargoes. Liner ships follow a fixed route within a fixed time schedule and serve many smaller customers. The schedules are usually published online and demand depends on the operated schedules. Hence, liner shipping services are comparable to train and bus services.

In the next section, we will discuss a variety of liner shipping problems on the strategic, tactical and operational planning levels, while Section 3 introduces some problems related to terminal operations. Sections 4 and 5 discuss respectively the influence of geographical bottlenecks and the importance of operations research in solving these problems. This overview is based on the following overview articles: Ronen (1983, 1993), Christiansen et al. (2004, 2007, 2013), Meng et al. (2014). In Section 6, a case study is performed for six Indonesian ports to provide insight into the different problems. Finally, conclusions are drawn in Section 7.

2 Container liner shipping

We will focus on the liner shipping operations concerned with the transport of containers. Liner shipping operators face a wide variety of decision problems in operating a liner shipping network. First, at the strategic planning level, the fleet size and mix problem and the market and trade selection problem need to be solved. In the fleet size and mix problem, operators decide on the fleet composition and in the market and trade selection problem on which trade route to serve. At the tactical planning level the network needs to be designed, prices need to be set and empty containers have to be repositioned. Finally, at the operational level, operators need to determine the cargo routing through the network and how to deal with disruptions. Furthermore, they can make adjustments to the earlier set prices and need to determine a plan to store all the containers on the ship during the loading process. These problems are considered in respectively the cargo routing, disruption management, revenue management and stowage planning problems. Some problems have to be considered at both the tactical and the operational planning level, such as setting the sailing speed and optimizing the bunkering decision and designing a (robust) schedule. In this section, we will introduce all these decision problems. In these problems we will make use of the following terminology. Liner shipping operators will also be referred to as liner shipping companies, liner companies or liners. Liner ships follow fixed routes, which are sequences of port calls to be made by the ship. Route networks consist of a set of services, which are routes to which a ship is allocated. Besides publishing their route networks, liner companies also publish the exact arrival and departure days at each port of call. When we refer to the route together with the arrival and departure days, we will talk about a schedule. Finally, a round tour refers to one traversal of a route and a (sea) leg refers to the sailing between two consecutive ports.

2.1 Strategic planning level

The strategic planning level consists of long term decision problems. Generally, these problems are only solved at most once a year. Examples of long term decision problems in container liner shipping are: the fleet size and mix problem and the market and trade selection problem.

2.1.1 Fleet size and mix

In the fleet size and mix problem, a liner company decides on how many ships of each type to keep in its fleet. Container ship sizes have increased substantially because of the growth in container trade and because of competitive reasons. For example, the Emma Maersk (introduced in 2006) has an estimated capacity of more than 14,500 TEU. Before the introduction of the Emma Maersk, the capacity of the largest container ship in the world was less than 10,000 TEU. In 2013, Maersk introduced a series of ships belonging to the Triple E class with capacities of over 18,000 TEU, while both MSC and CSCL introduced container ships with a capacity of more than 19,000 TEU in 2015. Ships benefit from economies of scale when they are sailing at sea, but they might suffer diseconomies of scale when berthing in ports. However, the effect of the economies of scale at sea is much larger than the effect of the diseconomies of scale in ports (Cullinane and Khanna 1999). Hence, economies of scale in larger container ships can lead to substantial savings if the capacity of the ship is adequately used. However, if the demand decreases and the liner company is not able to fill these large ships any more, higher operational costs are incurred by these large ships. Therefore, fleet size and mix problems are used to balance the possible benefits from economies of scale with the risk of not being able to use the full capacity of the ships. Since building a new container ship may take about one year and ships usually have life expectancies of 25-30 years, future demand and availability of ships play an important role in the fleet size and mix problem. Pantuso et al. (2014) present an overview of research conducted on the fleet size and mix problem. Most of these works incorporate ship routing and/or deployment decisions in order to ensure feasibility of demand satisfaction and capacity constraints.

2.1.2 Market and trade selection

Before a liner container shipping company starts building a network and operating the routes, it has to decide which trade lanes to participate in. The Asia-Europe trade lane is an example of a popular trade lane. Clearly, the selected trade lanes influence the type and number of ships required. For example, trade lanes serving the US will usually not use vessels from the Maersk Triple E class, since they can not sail through the Panama Canal and most ports in the US are not capable of handling these large vessels. Furthermore, the type and amount of cargoes that have to be transported and the required sailing frequency may influence the ship types used on the trade lane.

2.2 Tactical planning level

Medium-term decision problems belong to the tactical planning level. Liner companies usually change their service networks every 6-12 months, but more often in case of worldwide disruptions. Problems that have to be solved again each time the service network is adjusted are considered to belong to the tactical planning level. The examples that will be discussed next are: the network design problem, the pricing problem and the empty container repositioning problem.

2.2.1 Network design

The network design problem in liner shipping can be split into two subproblems. The first subproblem is the routing and scheduling problem, which is concerned with determining which ports will be visited on each route, in which order the ports will be called at and what the arrival and departure times at each port will be. Many studies only consider the routing decisions in the network design problem and do not address the scheduling problem of determining the actual arrival and departure time. The second subproblem considers the fleet deployment and frequency. Here, the liner company determines which ships will be used to sail each route and with what frequency the ships will call at the ports along the route. In general, a weekly frequency is imposed, which facilitates planning by shippers, but this can be relaxed to a biweekly frequency for low demand routes or multiple port calls per week for high demand routes. Sometimes sailing speed optimization is considered as a third subproblem of the network design problem, but in most studies the sailing speed is either assumed to be fixed and known, or will follow directly from the imposed frequency. Usually, the cargo routing problem is already included (using expected demand as input) in the network design problem in order to evaluate the profitability of a service network. The cargo routing problem will be discussed in more detail with the operational planning level problems.

The structure of the routes in a network can be divided into several types, like non-stop services or end-to-end connections, hub and spoke systems, hub and feeder systems, circular routes, butterfly routes, pendulum routes and nonsimple routes (?Brouer et al. 2014a). A non-stop service or end-to-end connection provides a direct connection between two ports: a ship sails from one port to the other and immediately back to the first port; sometimes this is called a shuttle service, although that also requires a high frequency. In a hub and spoke system, usually one port is identified as the main or hub port. All other ports (also called feeder ports) are served using direct services from the hub port. However, it is also possible that multiple hubs are applied, which are connected with each other and used as transshipment ports to satisfy demand between different feeder ports, in which case they might also be referred to as main ports. In the hub and feeder system, feeder ports might also be visited on routes with multiple port calls. Circular routes are cyclic and visit each port exactly once, while butterfly routes allow for multiple stops at the same port in one cycle. Pendulum routes visit the same port in both directions, only in reverse order. Finally, ports can be visited multiple times on nonsimple routes. Examples of some of these route types are provided in the case study in Section 6.

The liner shipping network design problem has attained quite some attention in the literature. We will briefly describe some of the recent publications on this problem. Plum et al. (2014b) consider a subproblem of the network design problem. They develop a branch-and-cut-and-price algorithm to find a single vessel round trip. Each port has to be visited exactly once and the best paying demand pairs are accepted and transported. Polat et al. (2014) consider an adapted neighbourhood search method to solve a hub and feeder system with one single hub. Finally, Zheng et al. (2015) propose a genetic algorithm to solve the same problem with multiple hubs.

Wang and Meng (2014) propose a column-generation heuristic approach to find the best liner shipping network. Each port can be visited twice during each route: once on the inbound direction and once on the outbound direction. Brouer et al. (2014a) provide both a base mixed integer programming formulation for the network design problem and benchmark data instances. They propose a column generation approach to generate butterfly and pendulum routes. Plum et al. (2014c) extend the butterfly routes as used in the benchmark model to routes with multiple butterfly ports. Brouer et al. (2014b) propose a matheuristic to solve the base network design problem with nonsimple routes. Although their assumptions are a bit more restrictive than in the benchmark paper (Brouer et al. 2014a), they are able to construct a more profitable route network using this approach.

Liu et al. (2014), Mulder and Dekker (2014) and Wang et al. (2015) consider slightly different network design problems. Liu et al. (2014) consider a problem in which the port-to-port demand is combined with the inland transportation. They start with an initial liner network and try to improve it while also including the transportation between the ports and the real origin and destination of the demand. Mulder and Dekker (2014) consider the strategic liner shipping network design problem, including the fleet size and mix problem, using a hub and feeder network structure. Wang et al. (2015) consider the liner shipping network alteration problem. In this problem, an initial liner network is given and this network is modified to become more profitable.

2.2.2 Pricing

The goal of liner companies is to maximize profit by transporting containers from one port to another. The revenue of the company is determined by the amount of containers that are transported and the price that will be charged for each container. The pricing problem is concerned with which price to charge for each possible demand pair. Factors that influence the price are for example: distance, trade direction, expected demand and expected capacity. The pricing problem is more a marketing, micro-economic problem than an operations research problem. Although it is an interesting problem, it has hardly been touched. Two approaches exist: cost-plus and what the market can pay. Yet, even determining the cost is a difficult allocation problem.

2.2.3 Empty container repositioning

Containers delivering import products in a region can be re-used to transport export goods to another region. However, most regions face an imbalance between import and export containers. This trade imbalance results in an excess of empty containers in regions with more import than export and a shortage of containers for high export regions. The empty container repositioning problem tries to reallocate the empty containers in order to solve the imbalance, where costs are associated with transporting a container from one region to another. The repositioning of empty containers is considered to be very costly, since there is no clear revenue associated with it.
Some recent papers dealing with the empty container repositioning problem are the following. Both Di Francesco et al. (2014) and Long et al. (2015) consider the empty container repositioning problem under uncertain container demand and use a stochastic optimization approach to solve it. Zhang and Facanha (2014) consider the problem of repositioning empty containers to the location of demand in the US. Empty containers are transported using trucks or trains to the location where they can be loaded. If containers can not be allocated to a loading location, they are transported to a West Coast port to be shipped to Asia. Huang et al. (2015) consider the network design problem with both laden and empty container repositioning. Multiple hub ports are identified, where transshipment from feeder ports might take place. They select the best routes from a candidate set of routes, which is used as input in the model.

2.3 Operational planning level

The operational planning level captures the problems that occur during the execution of the routes in the service network. In order to solve operational level problems, reliable information about the actual situation is needed. Hence, operational problems usually need to be solved relatively shortly before the solutions have to be implemented. Next we will discuss the cargo routing problem, the disruption management problem, the revenue management problem and the stowage planning problem.

2.3.1 Cargo routing

The cargo routing problem takes the liner shipping network and container demand as an input. The goal of this problem is to find a cargo flow over the network, satisfying the capacity constraints imposed by the allocated container ships, that maximizes the profit of transporting the containers. Costs are associated to (un)loading and transshipment operations. A transshipment occurs when a container has to be unloaded from a ship and loaded to another ship in order to arrive at its destination. Additionally, penalties can be imposed for demand that is not met. It is also possible to include transit time constraints to guarantee that containers will arrive on time at their destination.
Formulations of the cargo routing problem can be distinguished in OD-based link flow formulations, origin/destination-based link flow formulations, segment-based flow formulations and path-based formulations (Meng et al. 2014). All flow formulations consider the amount of flow at a link or segment of the route as decision variables in the model. Flow balance constraints ensure that all flow starts at the origin port and arrives at the destination port, but the exact route followed by a container might not be immediately clear from the model. In the OD-based link flow formulation, both the origin and the destination of the container are stored for each link in the network, while the origin/destination-based link flow formulations only store the origin or destination of the container. In this way, the number of decision variables can be reduced significantly. In a segment-based flow formulation, consecutive links of a route are already combined into segments before building the model. Segment-based flow formulations reduce the number of decision variables even more, but limit the possibility of transshipment operations to the ports at the beginning and end of the predefined segments. Finally, in path-based formulations complete container paths from origin to destination are generated beforehand and used as decision variable in the model. These paths might also include transshipment operations. The disadvantage of path-based formulations is that the number of paths might explode, such that more complex methods, like column generation, are needed to solve the problem. However, path-based formulations can usually be solved faster than flow-based formulations. Furthermore, transit time constraints are easily incorporated in path-based formulations, while this is generally much more troublesome in flow-based formulations. Little research is performed on the separate cargo routing problem: usually it is considered as a subproblem of the network design problem. Recently, Karsten et al. (2015) considered the cargo routing problem with transit time constraints. They propose a path-based formulation exploiting the ease to include transit time in this type of model. Their findings show that including transit time constraints in the cargo routing model is essential to find practically acceptable container paths and does not necessary increase computational times.

2.3.2 Disruption management

During the execution of the route schedules, ships may encounter delays. The disruption management problem focuses on which actions should be taken in order to get back on schedule after a disruption has occurred. Examples of actions that might be performed are: changing the sailing speed, swap port calls, cut and go (leave the port before all containers are (un)loaded) or skip a port. Usually, the goal of disruption management is to find a sequence of actions with minimum cost such that the ship will be back on schedule at a predetermined time. Brouer et al. (2013) propose a mixed integer programming formulation to solve this problem and prove that the problem is NP-hard. However, experimental results show that the model is able to solve standard disruption scenarios within ten seconds to optimality.

2.3.3 Revenue management

At the operational level, more information about the demand and available capacity of a ship is available. Therefore, it might be profitable for liner companies to vary their prices based on the available capacity between a port pair. Liners will probably charge higher prices related to low capacity pairs, while they might reduce the prices on legs where the available capacity is high.

2.3.4 Stowage planning

The stowage planning problem determines at which location containers are stored on the ship during the loading process. The stowage planning is a very complicated process with many constraints. Essential constraints are for example the stability of the ship both during the next sea leg and during the (un)loading process. Furthermore, containers may have to be stored at specific locations on the ship, like reefer containers. However, the storage of the containers also influence the (un)loading process in the next ports. Ideally, all containers with destination in the next port are stored on top of the stack, but this may take too many movements in the current port. Hence, a trade-off between the number of moves required to store and to discharge a container has to be made. Tierney et al. (2014) prove that the container stowage planning problem is a NP-complete problem.

2.4 Both tactical and operational level

Finally, some problems can either be considered at two different planning levels or have to be considered at two planning levels at the same time. For example, sailing speed optimization and bunkering optimization can be considered at the moment a new service network is designed, but the solutions to these problems can be reconsidered during the execution of the routes. Furthermore, robust schedule design is an example of a decision problem that combines decisions to be taken at the tactical and at the operational level.

2.4.1 Sailing speed and bunkering optimization

Both sailing speed optimization and bunkering optimization are typical problems that can be considered at two different planning levels. At the tactical planning level, the environmental aspects of sailing speed are usually considered. At the operational level, sailing speed is mostly used as an instrument to reduce delays incurred by the ship. The bunkering optimization problem is concerned with deciding at which ports ships are going to be refuelled. Initially, a bunker refuelling plan is made given estimates of the bunker price at the moment the ship will be at a bunkering station. Shipping lines also regularly make bunkering contracts, containing the ports where bunker can be purchased, the amount to be purchased, the price to be paid and the validity duration of the contract (Pedrielli et al. 2015). However, due to fluctuations in prices or fuel consumption, this initial plan might have to be adjusted at the operational planning level. At this stage, more accurate information about the fuel prices and availability at the ports and the bunker level of the ship is available. Sailing speed plays an important role in the bunker fuel consumption of ships and hence sailing speed optimization is often included in the bunkering optimization problem (Yao et al. 2012).

Recently, the sailing speed and bunkering optimization problems have received increasing attention. Psaraftis and Kontovas (2014) consider the speed optimization problem at the operational planning level. They include fuel prices, freight rates, cargo inventory costs and fuel consumption dependencies on payload into their model. Kontovas (2014) and Du et al. (2015) consider the influence of sailing speed on fuel emissions. Wang et al. (2013) provide a literature review on bunker consumption optimization problems. Bunker consumption is an important input for bunkering optimization. Yao et al. (2012) study the bunker fuel management strategy for a single liner shipping route. The strategy consists of the selection of the bunkering ports, the determination of the bunkering amounts and the adjustments in the sailing speeds. They consider a deterministic situation in which all parameters, including bunker costs, are fixed and known. Plum et al. (2014a) and Pedrielli et al. (2015) study the problem to determine the optimal bunkering contracts. Plum et al. (2014a) propose a mixed integer programming model, which is solved using column generation. Also, the possibility to purchase bunker on the spot market is included in their model. Pedrielli et al. (2015) use a game theoretical approach to design the contracts. Wang et al. (2014) propose a fuzzy approach to include uncertainties in the bunkering port selection problem. Their method returns a ranking of ports based on the profitability to bunker in these ports. Sheng et al. (2015) implement an (s, S) policy to jointly optimize the bunkering and speed optimization problem taking into account both bunker price and consumption uncertainty. Finally, Wang and Meng (2015) consider the robust bunker management problem, taking into account that the real sailing speed might differ from the planned sailing speed.

2.4.2 Robust schedule design

Robust schedule design can be seen as a combination of the scheduling problem at the tactical level and disruption management or sailing speed optimization at the operational level. The order in which ports are visited is considered to be an input of this problem. The goal is to jointly determine the planned arrival and departure times in each port and the actions that will be performed during the execution of the route when delays are incurred. The difficulty of this problem is that the tactical and operational planning level problems can not be solved separately, but have to be considered simultaneously.

The problem to determine the scheduled arrival and departure times under uncertainty in port times and a predetermined sailing speed policy is considered in Qi and Song (2012) and Wang and Meng (2012). Qi and Song (2012) provide some useful insights in the optimal schedule under 100% service level constraints. Wang and Meng (2012) formulate the problem as a two-stage stochastic programming problem and solve it using sample average approximation. They are able to find solutions with an objective value within 1.5% of the optimal solution in less than one hour.

3 Terminal operations

Liner shipping operations are closely related to terminal operations and decisions about ships cannot be taken while disregarding their effects on terminals. In fact, terminals are the largest bottleneck for shipping. It is important to have the right berth slots and to be loaded and unloaded quickly and in a predictable manner. There are many ports all over the world with a large number of ships waiting in front of the harbour to be allowed to berth. Accordingly we will discuss those terminals operations aspects which directly affect shipping, viz. berth scheduling, crane allocation and container stacking.

3.1 Berth scheduling

Both at a tactical as well as at an operational level, liner shipping schedules are made while taking berth availability into account. On a tactical level, when designing the liner shipping routes, agreements are made with terminals on berth availability and productivity (how many cranes and crane teams will be employed and how many container moves will be done per hour). This enables the shipping line to calculate the port time of his ships and to complete the ship scheduling. Naturally buffer times are incorporated in the schedule and in the berth schedule in order to take care of schedule deviations. Quite often agreements are made on demurrage charges (penalties related to delayed cargoes) if terminals need more time or if the shipping line arrives too late at the terminal. At the operational level the berth schedule is adjusted according to actual information. Quite often liner ships are too late. In 2015 Drewry shipping reports that ships are on average one day late. So the berth schedule is updated at a relatively short term (2 weeks) to take care of changing circumstances, while taking the tactical berth planning as a start.

3.2 Crane allocation

One level deeper than berth scheduling is the crane allocation. Cranes are used to move a container from the quay to the location where it will stored on the ship and vice versa. The storage locations on the ships are called locks. As container ships typically visit many ports, the cargo destined for a particular port will be distributed over many holds in the ship. After unloading, a ship will load cargo for several destinations which all have to be put in different ship holds. As a result the scheduling of the cranes is a difficult stochastic problem (handling times of containers are quite variable). The last crane to finish determines the moment when the ship can leave and hence the port time. A good balancing of the workload between the cranes is therefore necessary, but also very difficult to achieve. Another complication comes from the fact that port workers often work in shifts with fixed starting and end times, and a terminal will have to accommodate these restrictions.

3.3 Container stacking

A final aspect we like to mention is the stacking of the containers in the yard. The issue is not only that containers are stacked on top of each other, which complicates the retrieval of a bottom container, it is also the location on the yard of the containers to be loaded. If a ship moors right before the place where its (to be loaded) containers are located, then travel distances to the quay cranes are short and no bottlenecks are likely to occur. However, if a ship (due to delay or congestion at the berths) berths somewhere else, or if containers are spread out over the yard, then the terminal has to transport the containers over longer distances by which the loading could potentially be delayed. Container stacking is closely related to stowage planning, as the latter determines the order in which containers are to be loaded. In a perfect world one can take the order in which containers are stacked into account while making the load planning, but that creates a very complex problem, which also suffer from the variations in the loading. Hence costly reshuffles, where top containers are placed somewhere else to retrieve bottom containers are needed in large quantities.

4 Geographical bottlenecks

Canal restrictions form the main geographical bottlenecks for container ships. The Suez Canal and the Panama Canal are two well known canals imposing restrictions on container ships. The type of restrictions may differ between different canals. The main restriction imposed by the Suez Canal is for example the compulsory convoy passage through the canal. This results in long waiting times if a container ship misses the planned convoy. The Panama Canal on the other hand, imposes limits on the size of ships that want to sail through the canal.

Two other examples of geographical bottlenecks are the Strait of Malacca and the Gulf of Aden. These waterways are narrow, but are strategically important locations for the world trade, making them vulnerable to piracy.

Finally, ports may also impose geographical bottlenecks. Large ships might not be able to access certain ports, because the access ways have tight draft restrictions.

5 Operations research in liner shipping

In 1983, Ronen provided the first overview paper on the contribution of operations research methods in ship routing and scheduling. Since this first paper, every decade a follow-up overview paper appeared reviewing new research conducted in that decade (Ronen 1993, Christiansen et al. 2004, 2013). Initially, the reviews were mainly focused on the ship routing and scheduling problem, but more and more other shipping problems are included in these reviews. Furthermore, Christiansen

et al. (2007) provides an extensive overview of maritime transportation problems. Finally, Meng et al. (2014) give an overview of research related to container routing and scheduling in the liner shipping industry in the last thirty years. The number of citations in these reviews has increased fast, showing the increasing interest in operations research in liner shipping problems.
Liners usually face complex problems, because the above discussed decision problems cannot be seen separately from each other and because problem instances are usually large. For example, when a liner company wants to determine its service network, it has to consider which effect the included routes will have on the cargo routing problem. The solution to the cargo routing problem depends on the underlying network and will influence the profit of that network. This increases the complexity of the problems faced by liners, since they need to solve multiple decision problems simultaneously. Furthermore, the number of ports that need to be included in a network is usually large (it can easily contain over 100 ports). The Indonesian case study in the next section will show that designing a network for only six ports is already quite difficult. Liner companies used to solve these problems manually, but in the last years computerized decision support systems became available. A well-known example of a successful decision support system is TurboRouter, a tool for optimizing vessel fleet scheduling (Fagerholt and Lindstad 2007).

6 Case study: Indonesia

Shipping is an important mode of transport in Indonesia because the country consists of many islands. Figure 1 shows six main ports in Indonesia. The six ports are located on five different islands of Indonesia, hence transport over land is only possible between Jakarta and Surabaya. Transportation between all other combinations of these cities is only possible by sea or air.

Figure 1: Location of six main ports in Indonesia

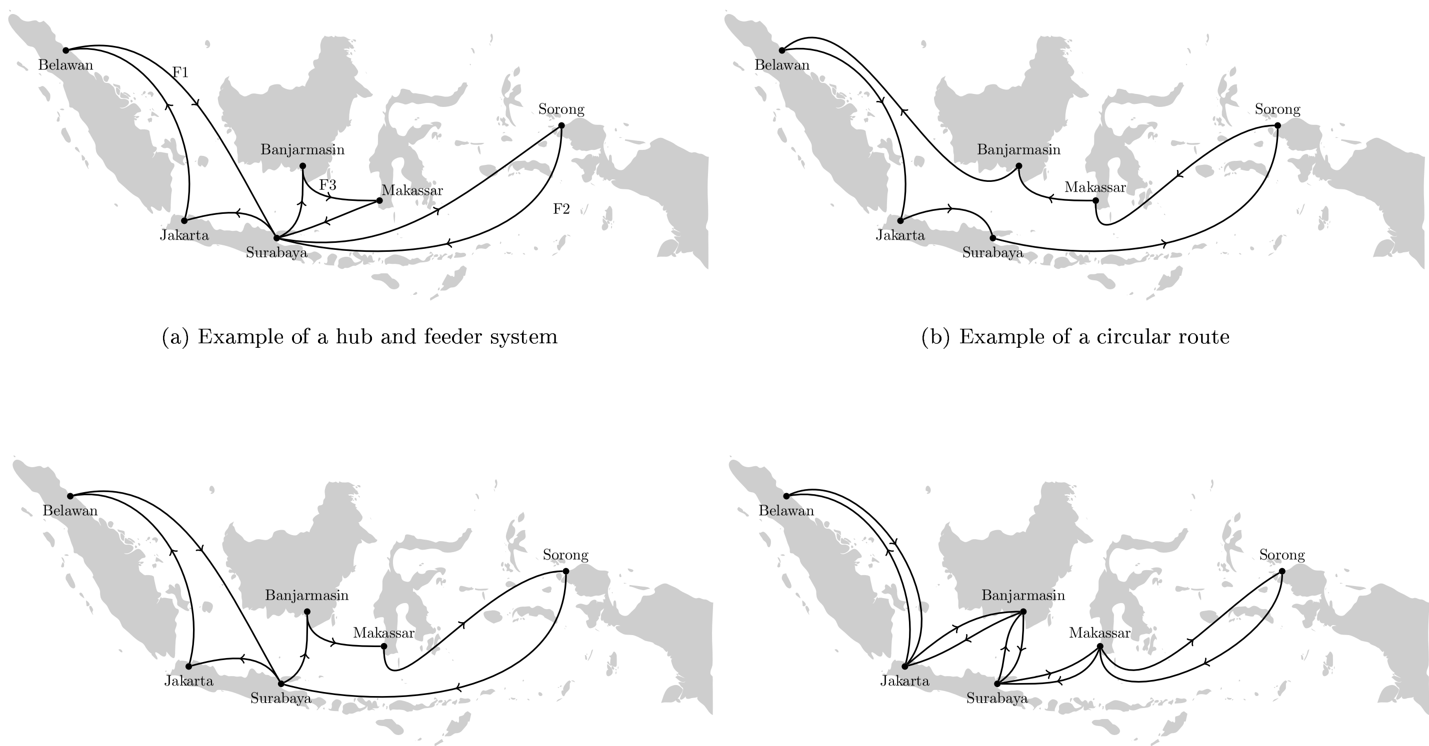
We will use the Indonesian case to illustrate some of the decision problems introduced in Section 2. Thereto, we will assume that Table 1 gives the expected weekly demand in TEUs between the Indonesian ports. The last column and row give the row and column sums, denoting respectively the total supply from and demand to a port. The supply and demand values denote the number of containers leaving and arriving in the port respectively. The difference between demand and supply indicates how many empty containers have to be repositioned from or to the port. For the six ports in Indonesia, the empty container repositioning problem is of limited importance, since there are no large differences between supply and demand.

	Belawan	Jakarta	Surabaya	Banjarmasin	Makassar	Sorong	**Supply**
Belawan	-	6,500	1,000	100	75	25	**7,700**
Jakarta	6,750	-	2,000	4,000	2,800	450	**16,000**
Surabaya	1,000	2,500	-	3,750	4,800	2,150	**14,200**
Banjarmasin	100	3,600	3,500	-	10	0	**7,210**
Makassar	100	3,500	4,000	75	-	0	**7,675**
Sorong	50	650	2,000	0	0	-	**2,700**
Demand	**8,000**	**16,750**	**12,500**	**7,925**	**7,685**	**2,625**	**55,485**

Table 1: Expected weekly demand in TEU between the Indonesian ports (Source: own calculations)

Table 1 shows that Jakarta and Surabaya are the two ports with the largest container throughput, while trade with Sorong is relatively small. In this specific case, this might lead to problems, since Sorong is also located relatively far away from the other ports. Liner shipping companies prefer to offer services calling at the ports of Jakarta and Surabaya and consider it too costly to call at Sorong. By charging higher prices for containers that have to be transported from or to the port of Sorong, liners can make stops at Sorong more attractive. Hence, the liner company may use the pricing strategy to ensure that services calling at Sorong will also be beneficial. However, to determine exactly which prices they have to charge in order to maximize their profit, the liner company needs more details on the cost structure of the network they will provide.

Figure 2 shows examples of a hub and feeder system, a circular route, a butterfly route and a pendulum route calling at the six Indonesian ports. In the hub and feeder system of Figure 2a the port of Surabaya is the hub port, while Belawan, Jakarta, Banjarmasin, Makassar and Sorong are feeder ports. The route Surabaya - Jakarta - Belawan - Surabaya is referred to as F1. F2 is a direct feeder route between Surabaya and Sorong. The third feeder route, F3, calls at Surabaya, Banjarmasin and Makassar after which it returns to Surabaya. The circular route in Figure 2b has as characteristic that each port is called at exactly once during the round tour. Figure 2c shows the butterfly route Belawan - Surabaya - Banjarmasin - Makassar - Sorong - Surabaya - Jakarta - Belawan on which Surabaya is visited twice. Finally, in the pendulum route of Figure 2d all ports are visited twice, only the second time in reversed order.



(a) Example of a hub and feeder system

(b) Example of a circular route

(c) Example of a butterfly route

(d) Example of a pendulum route

Figure 2: Route examples for the Indonesian ports

	Belawan	Jakarta	Surabaya	Banjarmasin	Makassar	Sorong
Belawan	-	1,064	1,488	1,430	1,708	2,807
Jakarta	1,064	-	438	614	806	2,102
Surabaya	1,488	438	-	328	520	1,816
Banjarmasin	1,430	614	328	-	353	1,577
Makassar	1,708	806	520	353	-	1,375
Sorong	2,807	2,102	1,816	1,577	1,375	-

Table 2: Distances between the Indonesian ports in nmi (Source: www.ports.com/sea-route/)

Table 2 shows the distances in nautical miles (nmi) between the six Indonesian ports and Table 3 provides some characteristics of five ship types. Types 1, 2, 3 and 5 are obtained from Brouer et al. (2014a), while Type 4 is suggested by the Indonesian government and costs are obtained using interpolation. Note that the fuel usage in ton/day of Type 4 is larger than the usage of Type 5, because Type 4 has a higher design speed than Type 5. These data can be used to get some insight in the route cost using different ship types and network structures. In the calculations we use a simplified version of the fuel cost function as provided in Brouer et al. (2014a):

$$F_s(v) = 600 \cdot \left(\frac{v}{v_s^*}\right)^3 \cdot f_s \tag{1}$$

Here, $F_s(v)$ denotes the fuel cost in USD per day for a ship of type s sailing at a speed of v knots (nmi/hour). v_s^* and f_s are the design speed and fuel consumption in ton per day of a ship of type s sailing at design speed and can be found in Table 3. Remark that the bunker cost varies over time, but is assumed to be constant and equal to 600 USD per ton in this study (Brouer et al. 2014a). Table 4 shows the route distance in nautical miles, the duration in weeks, the frequency, the number of ships required to obtain the frequency and the sailing speed in knots for each route. Distances can be found by adding the distances of the individual sea legs, while the duration and frequency are manually fixed in this example.

Ship type	Capacity (TEU)	Charter cost (USD/day)	Draft (m)	Min speed (knots)	Design speed (knots)	Max speed (knots)	Fuel usage (ton/day)
1	900	5,000	8	10	12	14	18.8
2	1,600	8,000	9.5	10	14	17	23.7
3	2,400	11,000	12	12	18	19	52.5
4	3,500	16,000	12	12	18	20	60.0
5	4,800	21,000	11	12	16	22	57.4

Table 3: Data of the ship characteristics (Source: Brouer et al. 2014a)

In liner shipping it is common to use weekly port calls at a route. Route durations are typically an integer number of weeks such that an integer number of ships is needed to sail this route. For example, a route with duration three weeks and which is sailed by three ships, ensures a weekly frequency. Given the duration and frequency, the number of required ships can be found by taking the product of these two values.

Route	Distance (nmi)	Duration (weeks)	Frequency (per week)	Required ships	Speed (knots)
F1	2,990	2	1	2	11.33*
F2	3,632	2	1	2	12.61
F3	1,201	1	1	1	12.51
Circular	6,476	4	1	4	12.27
Butterfly	6,862	4	1	4	13.62
Pendulum	7,802	5	1	5	13.55

Table 4: Route characteristics for the different ships (an * indicated that the speed is outside the feasible range for some ship types)

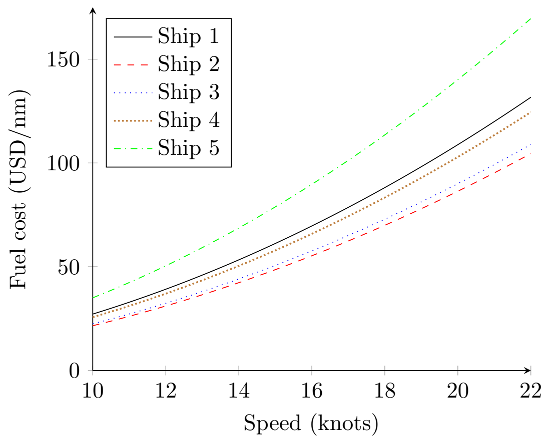


Figure 3: Fuel cost in USD per nautical mile

Figure 3 shows the fuel price in USD per nautical mile at different speeds for the five ship types. The fuel price is a convex function, meaning that when the speed is doubled, the fuel cost per nautical mile is more than doubled. Hence, a constant sailing speed during the route will minimize the fuel cost. The speed is calculated under the assumption that every port call takes 24 hours and the durations as given in Table 4. The following formula can then be used to determine the speed on each route:

$$v = \frac{\delta}{168 \cdot t - 24 \cdot n}, \tag{2}$$

where δ is the route distance in nautical miles, t the route duration in weeks and n the number of port calls on the route. An * in the column denoting the speed of Table 4 indicates that the speed is outside the feasible speed range for some ship types. The frequency is chosen in such a way that it is feasible for each ship type when sailing at maximum speed. Hence, the necessary speed can only be lower than the minimum speed of the ship type, in which case the ship will sail at minimum speed and will wait in one of the ports to obtain a weekly frequency.
Table 5 shows the weekly cost in USD for each of the routes given the frequency and duration as given in Table 4. The route costs consist of three components: the fixed ship costs, the port

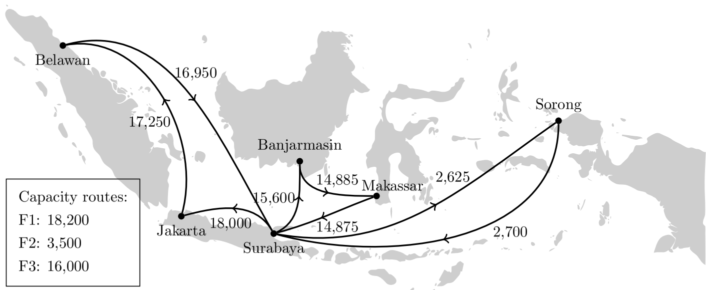
call costs and the fuel costs. When a liner company needs three ships to satisfy the required route duration and frequency, it bears weekly the fixed ship costs of all these three ships. Hence, the fixed ship cost is given by $7 \cdot S \cdot c_s^f$, with S the number of required ships and c_s^f the daily fixed ship cost of type s, which can be found in Table 3. The port call cost is the sum of the port fees of the ports visited on the route. If we assume that all port fees are the same, the port call cost is given by $F_p \cdot n \cdot q$, where F_p is the port fee per port visit and q the route frequency. In this example, we assume that $F_p = 650$ USD. The fuel cost is given by the product of the frequency, the number of days that a ship needs to sail one round tour and the fuel cost per day: $q \cdot \frac{\delta}{24 \cdot v} \cdot F_s(v)$, where $F_s(v)$ is the fuel cost in USD per day when sailing at speed v as given by (1). Consider a liner route with a duration of two weeks to which four ships are allocated. Each port on the route will then be called twice a week, resulting in a frequency of twice a week. Each ship needs two full weeks to sail a round tour, so in one week it will sail half of the route. Since there are four ships allocated to the route, in total two full round tours are made during a week (since the frequency is two). This explains the multiplication with the frequency in the fuel and port call cost. The total route cost in USD per week is now given by:

$$c_s^r = 7 \cdot S \cdot c_s^f + q \cdot \frac{\delta}{24 \cdot v} \cdot F_s(v) + F_p \cdot n \cdot q, \tag{3}$$

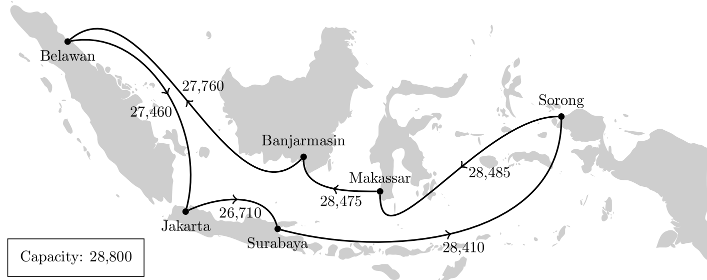
where c_s^r is the route cost in USD per week for a ship of type s. Doubling the capacity of a ship will not result in a doubling of the weekly route cost. This illustrates the effect of economies of scale: larger ships will in general have higher total costs, but lower costs per TEU, which is also exemplified in Table 6 by showing the weekly route cost per TEU under the assumption that the ship is fully utilized. The table also shows that the effect of economies of scale can differ quite a lot between ship types.

	Cost in USD/week				
Route/Ship	Type 1	Type 2	Type 3	Type 4	Type 5
F1	176,268	196,765	252,848	336,691	446,793
F2	228,411	238,026	285,297	373,868	497,669
F3	88,076	98,537	121,253	162,296	214,803
Circular	408,876	438,257	531,147	702,468	933,207
Butterfly	490,525	503,210	598,818	779,713	1,038,189
Pendulum	571,488	596,234	714,297	935,318	1,243,643

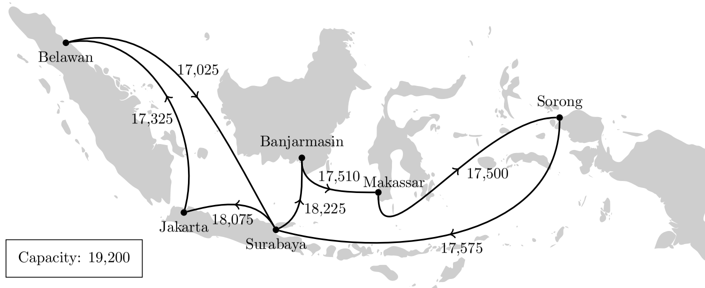
Table 5: Route cost per week for the duration and frequency as given in Table 4



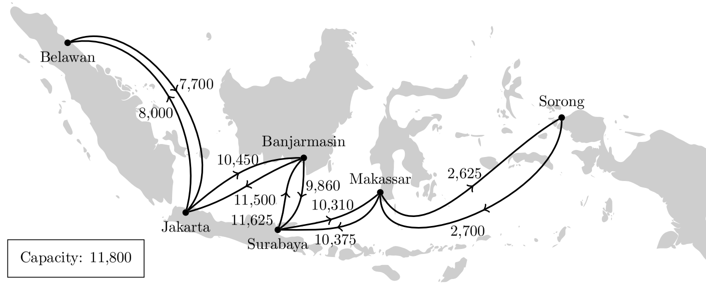
(a) Utilized capacities in TEU for the hub and feeder system



(b) Utilized capacities in TEU for the circular route



(c) Utilized capacities in TEU for the butterfly route



(d) Utilized capacities in TEU for the pendulum route

Figure 4: Route examples with utilized capacities

Route/Ship	Cost per TEU in USD/week Type 1	Type 2	Type 3	Type 4	Type 5
F1	196	123	105	96	93
F2	254	149	119	107	104
F3	98	62	51	46	45
Circular	454	274	221	201	194
Butterfly	545	315	250	223	216
Pendulum	635	373	298	267	259

Table 6: Economies of scale in ship size at full utilization

The disadvantage of the circular route is that the capacity can not be utilized efficiently. When containers from for example Surabaya to Jakarta are transported using the circular route, they will be on board of the ship on all sea legs except the leg from Jakarta to Surabaya. Butterfly routes are better able to utilize the available capacity, since some ports are visited twice on a round tour. In the butterfly route, the ports of Surabaya and Jakarta are visited directly after each other, such that the containers are only on board during one sea leg of the route. The pendulum route visits all ports twice, hence it needs the lowest capacity. In a hub and feeder network, usually many ports are connected by only one or a few sea legs. This ensures that hub and feeder networks are able to utilize the available capacity very efficiently. Figure 4 shows the utilized capacity at each sea leg in the four different route networks under the assumption that all demand has to be satisfied using only the given network. For the butterfly route, we assumed that the containers that have to be transported from Makassar to Banjarmasin will stay on board of the ship during the route segment Surabaya - Jakarta - Belawan - Jakarta - Surabaya. Alternatively, these containers can be unloaded during the first call at Surabaya and loaded again during the second port call at Surabaya in which case transshipment costs at Surabaya are incurred. The utilized capacities are found by adding all container flows that need to traverse the given sea leg in order to arrive at their destination. Table 7 shows the required capacity in TEU for each route, the number of port calls per week for each ship type in order to have enough capacity to satisfy all demand, the available capacity in TEU using these ship types and the total route costs in USD per week. The required capacity is found by taking the maximum utilized capacity of the route. Next, we make a combination of ship types such that enough capacity is available at each route. Given these ship allocations, the total route cost can be found by multiplying the weekly route cost for a ship type by the number of port calls per week divided by the route frequency. Note that the type and number of ships needed vary a lot between the three different route structures. For the hub and feeder system, $2 \cdot 1 + 1 \cdot 1 = 3$ ships of type 2 (since feeder route 1 has a duration of 2 weeks and feeder route 3 has a duration of one week), $2 \cdot 2 + 2 \cdot 1 = 6$ ships of type 4 and $2 \cdot 2 + 1 \cdot 3 = 7$ ships of type 5 are needed. The circular route uses $4 \cdot 6 = 24$ ships of type 5, while the butterfly route uses $4 \cdot 4 = 16$ ships of type 5. Finally, the pendulum route uses $5 \cdot 2 = 10$ ships of type 4 and $5 \cdot 1 = 5$ ships of type 5. Hence, the optimal solution to the fleet size and mix problem is highly dependent on the network structure.

Table 7 also shows the total network cost for the hub and feeder system, the circular route, the

Route	Req. cap. (TEU)	Port calls per week					Av. cap. (TEU)	Cost (USD/week)
		Type 1	Type 2	Type 3	Type 4	Type 5		
F1	18,000	0	1	0	2	2	18,200	1,763,733
F2	2,700	0	0	0	1	0	3,500	373,868
F3	15,600	0	1	0	0	3	16,000	742,948
HF-Total								**2,880,549**
Circular	28,485	0	0	0	0	6	28,800	**5,599,239**
Butterfly	18,225	0	0	0	0	4	19,200	**4,152,755**
Pendulum	11,625	0	0	0	2	1	11,800	**3,114,280**

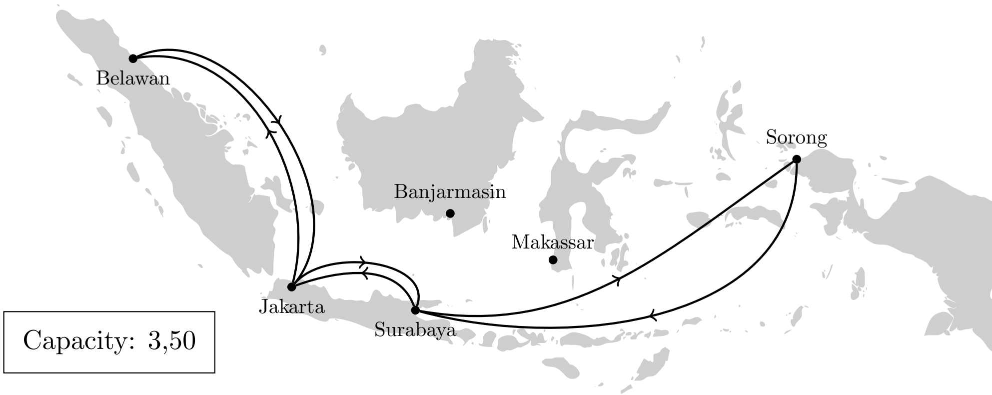
Table 7: Network cost per week when shipping all demand

butterfly route and the pendulum route. The table indicates that the hub and feeder system and the pendulum route are by far the cheapest choices of networks in this example. They both cost approximately 3 million USD per week, while the circular and butterfly routes cost respectively about 5.5 and 4 million USD per week. One remark has to be made: in the hub and feeder system, a lot of containers need to be transshipped, adding additional costs that are not included in this example. In total 15,450 containers have to be transshipped per week in the hub and feeder system. If a transshipment costs for example 100 USD per container, the total cost of the hub and feeder system will rise to almost 4.5 million USD per week. Hence, the hub and feeder system will then have higher costs than the butterfly and pendulum routes. Of course, one could also make route networks with combinations of these routes, which might be more cost efficient.

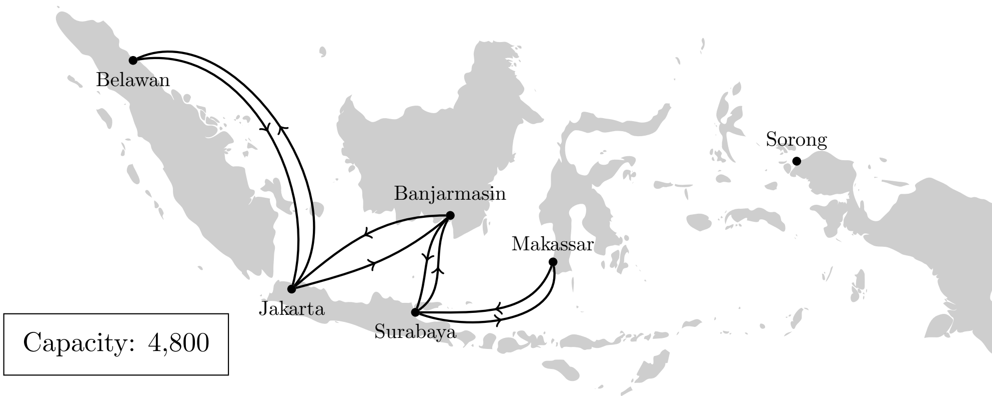
The good performance of the hub and feeder system and pendulum route is (partly) caused because of the better utilization of capacity in the hub and feeder system. Another advantage of hub and feeder systems is that liners can allocate different ship types to the different types of routes. Feeder ports usually have less demand than hub ports, hence it makes sense to allocate smaller ships to the feeder routes than to the main routes. If all ports are visited on similar routes, like circular, butterfly and pendulum routes, all these ports are visited by the same ship type. Hence, large ships might visit very low demand ports if these ships are able to berth in the smaller ports (smaller ports might have stricter draft restrictions than hub ports). Otherwise many small ships are needed in order to satisfy the demand of the large ports. However, a disadvantage of hub and feeder networks is that usually many transshipments are needed in order to satisfy the demand, which increases both the transportation price and transit time. In airline passenger transport, hub and feeder systems are very popular; an important reason for this is that transshipments are made by passengers at no apparent cost.

Finally, we determine the profit and efficiency of the networks when we assume that each container will generate a revenue of 200 USD if it is transported, (un)loading and transshipment costs are all 40 USD per container. Recently, the problem is also studied on request of the Indonesian government, resulting in a single pendulum route to be sailed. This pendulum route is also known under the name Pendulum Nusantara. We use the mixed integer programming model proposed in Mulder and Dekker (2016) to determine the optimal route network given an initial set of routes. Routes are constructed in the following way using the ordering of ports used for

(a) Route 1



(b) Route 2



(c) Route 3

Figure 5: Optimal route network

the pendulum route. Ports may be visited at most twice during a route: once on the eastbound trip and once on the westbound trip. All feasible routes are generated and given as input to the mixed integer programming problem, which makes use of a path formulation to solve the cargo allocation. Table 8 shows the profits of these networks and Figure 5 shows optimal route network. We see that the pendulum route performs indeed better than the hub-and-feeder network and the butterfly and circular routes. The efficiency of the networks is measured by the shipped distance in nmi per TEU. The shipped distance for direct shipping is equal to 836.57 nmi/TEU. Table 8 shows that the pendulum and optimal networks are both efficient networks with respect to shipped distance. Furthermore, the hub-and-feeder network is much more efficient than the circular and butterfly routes as expected.

The optimal route network as shown in Figure 5 consists of two pendulum routes (Routes 2 and 3) and a non-stop service (Route 1), which is a special type of pendulum route with only two port calls. The pendulum route structure ensures efficient transportation between all demand pairs. All routes have a frequency of once a week, reducing the number of required ships.

Network	Shipped distance (nmi/TEU)	Profit (USD)
Hub-and-feeder	1,428.06	3,159,651
Circular	3,269.79	1,058,961
Butterfly	2,227.57	2,284,445
Pendulum	996.80	3,642,916
Optimal	852.66	4,897,109

Table 8: Efficiency and profit of the different networks

7 Conclusion

Maritime transportation is very important in the world economy. The types of operations in the shipping market are distinguished in tramp, industrial and liner shipping. This chapter considers decision problems that occur in the operations of container liner shipping companies. The decision problems can be distinguished in three different planning levels: strategic, tactical and operational. The strategic planning level consists of long term decision problems, while the tactical and operational planning levels contain respectively medium and short term problems. This chapter discusses the fleet size and mix and market trade selection problem on the strategic level, network design, pricing and empty container repositioning on the tactical level and cargo routing, disruption management, revenue management and stowage planning on the operational planning level. Furthermore, sailing speed and bunkering optimization and robust schedule design are covered. These decision problems are related to both the tactical and the operational problem. The chapter also introduces three decision problems in the terminal operations that are related to container liner shipping: berth scheduling, crane allocation and container stacking. A case study is used to explain the concepts of the problems in more detail. The case study is based on six main ports in Indonesia. Three networks with different structures (hub and feeder system, pendulum route and butterfly route) are proposed. Calculations show that the cost of the hub and feeder system is much smaller than the cost of the other two networks when transshipment costs are not considered. Explanations for this result are that capacity is better utilized in hub and feeder systems compared to the other network structures and ships can be chosen more freely, since more shorter routes are used. When transshipments are charged at 100 USD per container, the hub and feeder system performs comparable to the butterfly route and still considerably better than the pendulum route.

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