Chapter 2

Maritime Transportation

The aim of this chapter is to introduce the reader to maritime transportation. In the following a short overview on numbers and figures of world trade, ocean going transportation and especially container ship transportation, which is the focus of this thesis, is given.

About 90% of world trade, in terms of volume, is transported on ocean going ships, which makes up 70% of world trade in terms of value (see Hoffmann 2008, p. 14). Within maritime transportation, ocean going ships can be mainly classified into bulk carrier which transport dry bulk products, tankers, carrying for example liquefied gas or crude oil, container ships, general cargo transporting ships and passenger ships. In terms of carrying capacity in tons, the majority of cargo can be transported by tankers with a share of 41.77% or 475.8 mil. dwt (deadweight tonnage, the ship carrying capacity measured in metric tons) followed by bulk carriers and container ships with 36.63% (417.2 mil. dwt) and 13.28% (151.3 mil. dwt) respectively. General cargo carrying ships account for 7.85% (89.4 mil. dwt) and passenger ships only for 0.48% (5.5 mil. dwt) (ISL 2011a, p. IV). In terms of value these figures slightly change because consumer goods have a high ratio of value per ton and are almost exclusivley transported by container (Stopford 2009, see p. 505 and 518). This makes container ship transportation the most important mode of ocean going transportation.

Figure 2.1 shows the yearly container handling for different regions of the world. Note, that between the years 2000 and 2008 the worldwide container handling activities have increased steadily. Only for the years 2001 and 2008 the annual growth rate was below 10%. With the beginning of the financial crisis in 2008 maritime container transportation dropped and finally in 2009, the container handling activities decreased by 8.9%. But in the future the annual growth rate is expected to rise by 10% or more. Latest figures state that the growth for the year 2010 was nearly 13% (ISL 2011b, p. 5).

V. Windeck, *A Liner Shipping Network Design,* Produktion und Logistik,
DOI 10.1007/978-3-658-00699-0_2, © Springer Fachmedien Wiesbaden 2013

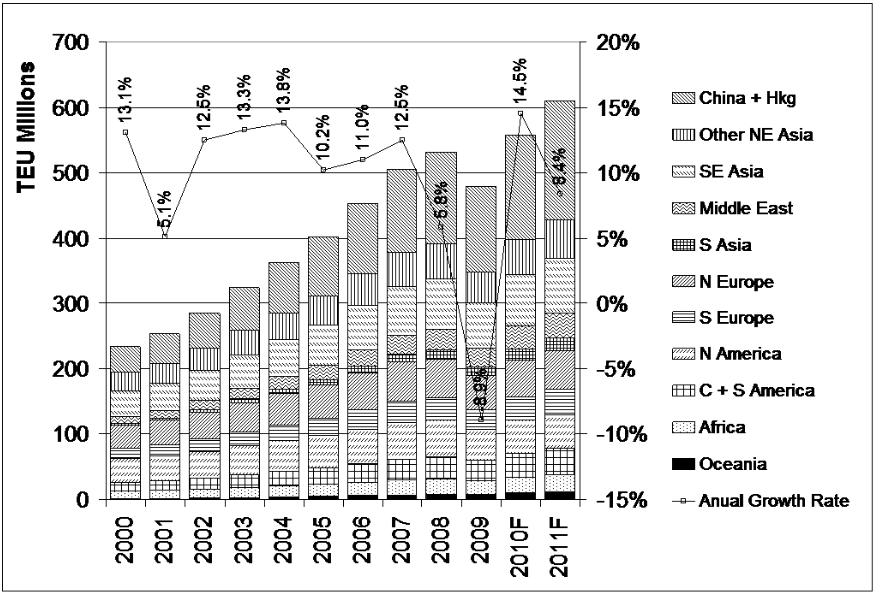

Figure 2.1: Global container handling from 2000 to 2009 and forecasts for 2010 and 2011, according to Tiedemann (2011)

In regard to regional growth of container handling activities, all regions show an increase in container handling activities for the years 2000 to 2011. Again only in the year 2009 all regions had a cutback in container handling activities. The growth rates for China and Hong Kong are the highest, followed by South East Asia.

The amount of container ships and their average container carrying capacity has been increasing steadily over the years. In the last 20 years the average carrying capacity of container ships increased from 1,250 TEU (twenty feet equivilant units) in 1990 to 2,880 TEU at the beginning of 2011 (ISL 2011b, p. 13). The Hamburg Index for Containership time-charter rates, classifies container ships into 9 different classes. Gearless ships are divided into three classes of 200 – 299 TEU, 300 – 500 TEU and 2,000 – 2,999 TEU carrying capacity. The other 6 classes of geared ships have carrying capacities between 200 and 1,999 TEU. The Hamburg Index is measured in dollars per 14-ton slot and day. 14 tons is the average weight of a loaded twenty feet container and therefore a slot is comparable to 1 TEU. This index shows decreasing charter rates for container ships beginning in the year 2008 and is only slowly increasing again in recent months. Since the development of charter rates is similar for all of the different container ship classes, only the gearless ship class with a carrying capacity of 2,000 – 2,999 TEU will be regarded as a representative for the charter rate development of all ship classes. Charter rates for this class fell from above 18 $ in year 2005 down to around 13 $ in 2008 and further down to only 2.1 $ in 2009. From then on, the prices slowly increased up to 6.2 $ in 2010 (ISL 2011a, p. 158). This shows, that charter rates for container ships have not fully recovered back to the pre-financial crisis level. A similar development can be seen for freight rates in the major liner trade routes where as an example, prices for containers transported between Asia and Europe fell from 1,837 $ per TEU in the third quarter of 2008 down to 897 $ per TEU in the second quarter of 2009 and have slowly increased to 1,422 $ per TEU in the fourth quarter of 2009 (Asariotis et al. 2011, p. 88).

Bunker fuel prices have a great impact on the development of the worldwide maritime transportation business and have been subject to change parallel to the world economic development. Due to the growing world economy and subsequently increasing transportation demand, oil and gas prices rose steeply before the financial crisis in 2008. In July 2008 bunker fuel (CST 180) was sold at 720 US $/MT in european harbours (average price for harbours Hamburg, Rotterdam and Le Havre) but dropped down to 236 $/MT in December 2008, the hight of the financial crisis. After that prices again steadily increased up to a new all time high of 735 $/MT in April 2011 (ISL 2011b, p. 74).

These statistics only show some of the many influencing parameters on maritime transportation and especially container shipping. To be able to quickly adapt to changing environments, decision support systems are needed, that account for as many of these interacting parameters as possible. Decision makers are then able to quickly reorganise their business based on those plans received with the objective to improve economic competitiveness.

2.1 Freight Transporation Systems

Generally transportation systems can be subdivided into land-based and water-based transportation or transportation by air. In the following we will only concentrate on freight transportation and not on passenger transportation. In many areas transportation systems compete for cargo but differ in transportation costs, capacity, speed, on time delivery, and the density of their network.

Road based transportation which is normally performed for example by trucks is more flexible and can operate in many areas. The network is very dense for most populated regions and costs for loading and unloading facilities and equipment are very low compared to other modes of transportation. Predominant restrictions for trucks are the relatively small capacity in regard to volume and weight. Additionally, governmental regulations on wheel times reduce the benefits of using this mode of transportation. A truck is, other than for example a ship, in almost all cases not operated around the clock. There is usually only one driver per truck, so that the truck will not be operated, when the driver has to have a mandatory rest period. On the other hand, trucks are especially cost and time effective for transporting individually packaged goods over short to medium distances. The advantage of water-based transportation is the ability of shipping bulk cargo and large volume cargo over long distances. With increasing distances trucks loose their advantage in favour of rail road transportation. In comparison to trucks a train has a more limited network to travel on, but is more energy efficient and therefore also more environmental friendly. The advantage of trains is the fast transportation of bulk cargo on long distances. The disadvantages are longer stops and cargo handling costs.

The fastest mode of transportation is by aircraft, on which mainly high priced goods with a high ratio of price to volume or weight are transported. As expected, the higher speed implies higher transportation costs. However, a higher speed is usually only achieved on longer distances. On short distances cargo handling times would add up to higher transportation times in total compared to trucks or trains for instance.

A lot slower but a cheaper mode of transportation than trucks, trains and aircrafts are ships. We distinguish between inland or river barges and ocean going ships. Where inland or river barges mainly compete with trucks and trains, in many cases, the only alternative to ocean going ships are aircrafts. For example, cargo can only be transported between Europe and Northern America or Asia and Northern America by ship or aircraft. Between Europe and Asia, cargo might be shipped by ocean going ships, aircraft or even by train via Russia. In the following, when mentioning ships, we will only consider ocean going ships. Even though there is a high potential for further decreasing emissions, ships are known to be environmentally friendly in comparison with other modes of transportation. The only drawbacks are that ships travel a lot slower than other vehicles and that they are restricted to harbours where they can load or unload cargo.

Christiansen et al. (2007, p. 192) compare many different characteristics of five different modes of transportation (see Table 2.1).

Operational characteristic	Mode				
	Ships	Aircraft	Truck	Train	Pipeline
Barriers to entry	small	medium	small	large	large
Industry concentration	low	medium	low	high	high
Fleet variety (physical & economic)	large	small	small	small	NA
Power unit is an integral part of the transportation unit	yes	yes	often	no	NA
Transportation unit size	fixed	fixed	usually fixed	variable	NA
Operating around the clock	usually	seldom	seldom	usually	usually
Trip (or voyage) length	days-weeks	hours-days	hours-days	hours-days	days-weeks
Operational uncertainty	larger	larger	smaller	smaller	smaller
Right of way	shared	shared	shared	dedicated	dedicated
Pays harbour fees	yes	yes	no	no	no
Route tolls	possible	none	possible	possible	possible
Destination change while underway	possible	no	no	no	possible
Harbour period spans multiple operational time windows	yes	no	no	yes	NA
Vessel-harbour compatibility depends on load weight	yes	seldom	no	no	NA
Multiple products shipped together	yes	no	yes	yes	NA
Returns to origin	no	no	yes	no	NA

NA – not applicable

Table 2.1: Comparison of operational characteristics of freight transportation modes (Christiansen et al. 2007, p 192)

Other than trucks and trains, ships usually have to pay a harbour fee and stay in a harbour for multiple operational time periods during loading and unloading operations. Additionally the amount of cargo loaded on board of a ship may decide on whether that ship can enter a harbour or not, due to its cargo weight dependent draught. Furthermore, weather and tides sometimes may restrict the call at a harbour. In many cases ships are travelling in international waters, which again leads, compared to trucks and trains, to higher operational uncertainties.

Despite their fundamental differences, ships and aircraft have much in common. Both are highly dependent on technological and economical developments and are to a great extent subject to weather uncertainties. The fixed size of the vehicles and their independence of a central depot are problems in common. With truck transportation the volume and carrying capacity can be changed by simply attaching a trailer. Differences can be seen in the way these two types of vehicles operate. A great portion of the air traffic is a combination of cargo and passenger transportation, where cargo is transported in an aircraft's belly. Since passengers preferably travel by day, this combined transportation usually takes place during daytime hours, whereas ships are operated 24 hours a day.

Finally, ships differ from all other transportation vehicles in their high diversity. In most cases ships are built unique. Only very few classes of ships are built in small series. Aircrafts vary only between a small amount of aircraft types, whereas the size of a truck is very much limited due to road restrictions in terms of hight, breadth, and weight. Therefore, only a couple of standard sizes have become accepted. Compared to trucks, rail road wagons have similar sizes but a whole train can vary in length. The shorter a train is, the less efficient its operation is. The total length of a train is limited by the total weight a rail road engine can pull, judicial restrictions and operational restrictions, like the maximum length of a rail way station.

In the shipping industry, ships are classified by their designated use. Bulk cargoes appear in liquid and dry shape. Tankers for example are built to transport liquids in bulk. Best known are crude oil tankers or liquefied gas tankers. The so called bulk carriers are designed to transport dry bulk, like iron ore or coal. Roll-on-Roll-off (Ro-Ro) ships are designed to allow cars and trucks to enter the ship via a ramp. Refrigerated ships are able to transport perishable goods. Bananas are a classical example, on long distances. Instead of transporting these goods on especially designed ships for transport of refrigerated freight on long distances, many perishable goods are nowadays being transported in reefers (refrigerated containers) on container ships. For this type of container, container ships need to have special storing positions with plugs for the electric power supply of the reefer containers.

On the other side general cargo ships are capable of transporting all kinds of cargo. These cargoes usually have a special size and must be handled separately. These ships often have on-board cranes for loading and unloading. The loading and unloading of this kind of cargo is in most cases very time and labour intensive. Other types of ships are ferries, cruise ships, naval and fishing ships. This thesis purely concentrates on container ships, which transport either standardized 20 feet or 40 feet containers. Containers are counted in 20 feet equivalent units (TEU), so that a 40 feet container counts for 2 TEU. The maximum load capacity of a TEU is 28 tons at a maximum volume of 1,000 cubic feet of volume (see Christiansen et al. 2007, p. 199).

2.2 Terms and Definitions

Ronen (1983) introduced a classification scheme for routing and scheduling problems in maritime transportation according to Lawrence (1972) where planning tasks are divided into industrial-, tramp- and liner-shipping problems.

Liner shipping operations can be compared to a bus line service. A characteristic of these maritime pick-up and delivery problems is that ships never return to a depot and proceed to operate on their assigned route according to a published schedule. Additionally, harbours within a single circling liner service might be called at more than once by the same ship, which is not solvable with standard routing models of land-based transportation (see Page 20).

Tramp shipping is comparable to a taxi service. Mainly spot cargo or project cargo is loaded as a full ship load at a specific harbour and delivered to the cargo's destination harbour. Where spot cargo is cargo that is picked up on a short term basis, and other than cargo a shipping company is obliged to transport under long-term contracts, can optionally been transported if capacity is still available on ships. Cargo of extraordinary size, like machines and larger vehicles, is referred to as project cargo. After delivery of the cargo, the tramp ship might have to travel empty to another harbour before loading the next cargo according to the next order.

Whereas in liner and tramp shipping the objective is to maximize profit, the aim in **industrial shipping** is to minimize costs. Usually ships operating in industrial mode are controlled by the owner of the cargo. These ships are often scheduled to operate according to the needs of a closed supply chain and have a vital part in the system.

When discussing maritime transportation planning problems, we always refer to water-side planning tasks. Land-side planning tasks, such as ship berth allocation and crane scheduling, container yard or ship management, are not discussed in detail in this thesis.

To further distinguish planning problems of maritime transportation, a distinction between strategic, tactical and operational problems will be made. Strategic problems are those with a longer planning horizon compared to tactical and operational problems.

Christiansen et al. (2007) assign

- market and trade selection,
- ship design,
- network and transportation system design,
- decisions for fleet size and mix
- harbour or terminal location, size and design

to the strategic planning problems.

Market and trade selections are understood as the shipping companies decision of which countries and regions and therefore markets to take into consideration for a harbour visit of its ships. In regard to container liner shipping this decision will be, which harbours of a specific liner service should be visited on a regular basis and which harbours should not be visited because no additional profit is expected.

Questions of a ship design problem might be the dimensions of a ship, length, breadth, draught and cargo holding capacity, a ship's service speed and therefore engine size and its transportation purpose. This decision has an impact on the harbours it can visit and the routes it can travel on. The draught of a ship might prevent a ship from entering a too shallow harbour and the length, breadth and draught of a ship might not allow for a canal passage. The maximum size of the panama canal locks is a threshold according to which ships are classified in panamax or post-panamax ships. Ships with post-panamax size cannot travel through the Panama Canal due to their size. Bigger ships like capesize ships are even too big to enter the larger Suez Canal and therefore have to travel around the Cape of Good Hope, the most southerly point of Africa.

A maritime network and transportation system design determines the harbours one or multiple ships of the same or different type are visiting according to their transportation task. This also includes the decision, which harbour to declare to operate as a transshipment harbour in a liner network environment.

Most of the published decision support systems for solving maritime transportation problems cover more than one of the above mentioned strategical planning problems. As will be shown later, solution approaches might spread across strategic and tactical problems or technical and operational problems. As an example the fleet size and mix decision problem which specifies the type, size and number of ships, is often solved in combination with a network and transportation system design. In this thesis the harbour or terminal location size and design will not be examined. In our strategic approach several harbours will be considered but will not have to necessarily be visited by a liner service. This thesis will determine the maximum profit generated and the specific number and type of ships, that can operate on developed liner round trips and schedules while transporting assigned cargo. The resulting combination of fleet size and mix, routing and scheduling and cargo assignment problem is classified as a strategic decision support system for this thesis.

Tactical planning problems in maritime transportation according to Christiansen et al. (2007) are again the

- adjustment of the size and mix of the fleet,
- fleet deployment,
- ship routing and scheduling and
- inventory ship routing

The fleet deployment task answers the question, which ships to assign to liner services or when thinking of industrial shipping, which ships to assign to specific trips according to a given order. Ship routing and scheduling is especially important for industrial and tramp shipping modes, where ”routing is the assignment of sequence of harbours to a vessel” and ”scheduling is assigning times to the various events on a ships route” (Ronen 1993, p. 326).

The models and decision support systems presented in this thesis span across a wide range of ship routing and scheduling tasks simultaneously. Which of these tasks are accounted for and which not, according to the classification by Christiansen et al. (2007, p. 196) is shown in Table 2.2.

Ships, mainly operating in closed supply chains and in industrial mode, have to prevent an out of stock situation at a delivery harbour and have to assure that production will not stop due to an already full stock at its assigned harbour. This task is part of the inventory ship routing.

Maritime Planning Tasks	Incorporated in this Thesis
Strategic	
Market and trade selection	incorporated (see Chapter 4)
Ship design	incorporated (see Chapter 4)
Network and transportation system design	incorporated (see Chapter 4)
Fleet size and mix decisions	incorporated (see Chapter 4)
Harbour or terminal location, size, and design	incorporated (see Chapter 4)
Tactical	
Fleet size and mix	incorporated (see Chapter 4)
Fleet deployment	incorporated (see Chapter 4)
Ship routing and scheduling	incorporated (see Chapter 4)
Inventory ship routing	not regarded
Berth scheduling	not regarded
Crane scheduling	not regarded
Container yard management	not regarded
Container stowage planning	not regarded
Ship management	not regarded
Distribution of empty containers	not regarded
Operational	
Cruising speed selection	incorporated (see Capter 3)
Ship loading	not regarded
Environmental routing	incorporated (see Capter 3)

Table 2.2: Strategic, tactical and operational planning tasks in maritime transportation according to Christiansen et al. (2007, p. 196)

Operational planning tasks concern the cruising speed, ship loading and environmental routing. When planning the cruising speed, the question is, which average speed has to be selected for the whole voyage between two harbours or which speed to select on single steps of the voyage. This might include travelling at a higher speed at the beginning of a voyage in order to circumnavigate poor weather conditions or vice versa and any combination of speed selections along the route. Usually a predefined latest time of arrival at the destination harbour is given and the objective is to either find a shortest time path or a minimum cost path. Environmental routing incorporates external influences on the ship's behaviour like wind, waves and ocean currents. This planning task is part of the operational routing problem presented in Chapter 3 of this thesis.

In terms of speed, ship owners started to operate their ships in so called slow steaming mode over the last years. This way significant savings in fuel costs can be achieved, since a reduction in speed by 20% reduces the fuel consumption by 50% per time unit (see Christiansen et al. 2007, p. 267). The understanding of the terms full speed steaming, slow steaming and super slow steaming might vary in the maritime transportation environment. In our case full speed steaming represents speeds of 23 ± 1 knots, slow steaming is 18 ± 1 knots and super slow steaming corresponds to 14 ± 1 knots. In practice, ships travel with a higher speed in the direction where the flow of goods is higher. In the opposite direction, ships usually travel slower.

2.3 Routing and Scheduling

A large amount of models that describe land-based vehicle routing and scheduling problems can be found in the corresponding literature. Before presenting models that account for the special characteristics of ships in Section 2.4 the reader is introduced to more general routing and scheduling problems. Some of the models presented might as well be used for modelling ship routing and scheduling problems, which is shown in the following. The easiest way of routing land-based vehicles like trucks is modelling the problem as a standard Vehicle Routing Problem (VRP) or any of its variants. A typical example for making use of an extended vehicle routing model formulation is to describe a parcel service. Usually parcels are distributed to a recipient from a central depot. In order to minimize costs, a parcel service will try to arrange the delivery to its recipients in such a way that the total distance travelled is minimized. With a given road or rail network, the task is to find a minimum distance trip that includes a visit to all potential costumers starting and ending at a given depot. In addition, such a service might also include the pick-up of cargo. This type of problem is called a pick-up and delivery problem, which is an extension of the classical VRP. Here cargo can be dropped off, picked up or both at each visiting point. For the example of a parcel service, customers of consumer goods may have the right to return for instance clothes that do not fit or electronic devices that have a failure within their warranty period. For these cases, companies might allow their customers to have their goods picked up by a parcel service and have them returned to the sender.

In the following a similar problem is described in detail, which has been presented by Karlaftis et al. (2009) as a ship routing problem. They designed a mixed integer programming model for their pick-up and delivery problem of containers. These containers have to be shipped between a central depot (a hub harbour) and many smaller harbours on islands in the Aegean Sea.

Sets and Indices

$k, v \in K$	Set of ship types
$i, j, h \in N$	Set of harbours
0	Depot, mainland harbour

Data

d_i	Demand at harbour i
c_{ijk}	Cost for traversing an arc from harbour i to j
q_k	Capacity of a ship of type k
t_{ijk}	Time for traversing an arc from harbour i to j by a ship of type k
s_{ik}	Necessary time to service harbour i by a ship of type k
tt_k^{max}	Maximum total travel time for a ship of type k
lta_j	Latest arrival time at harbour j
p_j	Pick-up load to be picked up in harbour j
m	Sufficiently large number

Variables

X_{ijk}	1, if a ship of type k is traversing an arc from harbour i to j; 0, otherwise
A_i	Arrival time at harbour i
L_{jk}	Cargo on board of a ship of type k after leaving harbour j

$$min : \sum_i \sum_j \sum_k c_{ijk} \cdot X_{ijk} \quad (2.1)$$

$$\sum_i \sum_k X_{ijk} = 1 \qquad \forall j \quad (2.2)$$

$$\sum_j \sum_k X_{ijk} = 1 \qquad \forall i \quad (2.3)$$

$$\sum_i X_{ihk} = \sum_j X_{hjk} \qquad \forall h, k \quad (2.4)$$

$$\sum_{j \neq 0} X_{0jk} \leq 1 \qquad \forall k \quad (2.5)$$

$$\sum_{i \neq 0} X_{i0k} \leq 1 \qquad \forall k \quad (2.6)$$

$$\sum_i \sum_j X_{ijk} \leq |Q| - 1 \qquad \forall k, Q \subseteq N/0, Q \geq 2 \quad (2.7)$$

Without the index k, the objective function (2.1) and constraints (2.2) to (2.3) plus constraints (2.7) represent a standard Travelling Salesman Problem (TSP). A recent review on the TSP has been provided by Laporte (2010). The objective function is to minimize the costs that arise when travelling on an arc connecting nodes i and j. Nodes for the TSP can be any customer that the salesman has to visit on his round trip. Every customer has to be visited once. In our case the customers are harbours a ship has to visit for loading or unloading activities. Costs for the TSP are often just the travelled distance. For a ship these costs might be the speed dependent fuel costs. Constraints (2.2) and (2.3) imply that every node or in our case harbour has to be visited and left again exactly once. The subtour elimination constraints in (2.7) are the ones presented by Dantzig et al. (1954). Better performing subtour elimination constraints have been developed by Miller et al. (1960) and Gavish (1978). For a comparison of these and newer developed subtour elimination constraints see Langevin et al. (1990). They compare subtour elimination constraints regarding their computational complexity. Subtour elimination constraints avoid multiple smaller round trips for a single vehicle, that are not connected among themselves as shown on the right side of Figure 2.2.

If we regard a node 0 as the home of the salesman, from where he wants to start his voyage and to where he wants to return again, we add constraints

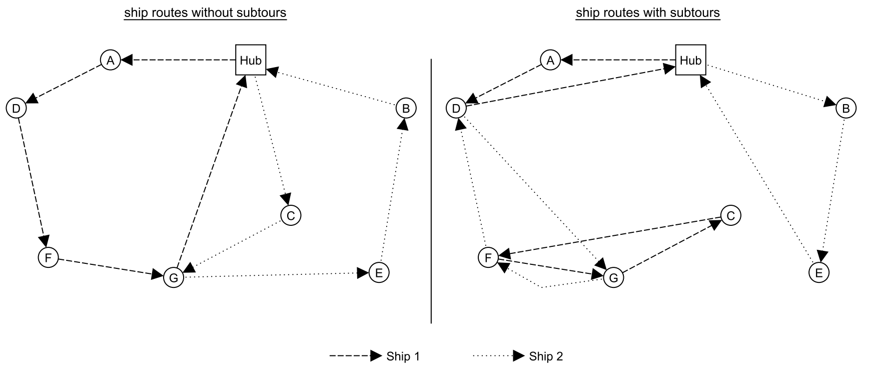

Figure 2.2: Ship routes without and with subtours

(2.5) and (2.6). These constraints force the salesman to start and to end at his origin 0. In case of vehicles this origin and final destination node is often called the depot of a vehicle. For our multiple vehicle case, we also have to assure that no vehicle has subtours and therefore constraints (2.7) have to be constructed for every vehicle or a ship of type k. With the following capacity constraints (2.8) we have a complete Vehicle Routing Problem VRP:

$$\sum_i d_i \left(\sum_j X_{ijk} \right) \leq q_k \qquad \forall k \qquad (2.8)$$

Here a demand d_i is picked up at harbour i if this harbour is visited, which is indicated by variable X_{ijk} and can only be transported, if the capacity q of a ship of type k is not exceeded by this additional demand. VRPs can be enriched by accounting for a permitted total travel time of vehicles as given in constraints (2.9) where the harbour and ship type specific necessary time for service (loading and unloading operations) s_{ik} is added to the arc and ship type dependent travel time t_{ijk}. The sum of service and travel times has to be smaller than a permitted total travel time for a ship of type k given by tt_k^{max}. A description of the development of the vehicle routing problem since its invention in 1959 by Dantzig and Ramser (1959) has again been provided by Laporte (2009).

$$\sum_i s_{ik} \sum_j X_{ijk} + \sum_i \sum_j t_{ijk} \cdot X_{ijk} \leq tt_k^{max} \qquad \forall k \qquad (2.9)$$

If a cargo either has to be picked up and dropped off at a given time or if harbours have specific opening times, Time Windows (TW) are used to describe these constraints (see constraints 2.10 to 2.13).

$$A_j \geq A_i + s_{ik} + t_{ijk} - (1 - X_{ijk}) \cdot tt_k^{max} \qquad \forall i, j, k \qquad (2.10)$$
$$A_j \geq A_i + s_{ik} + t_{ijk} + (1 - X_{ijk}) \cdot tt_k^{max} \qquad \forall i, j, k \qquad (2.11)$$
$$A_0 = 0 \qquad (2.12)$$
$$A_i \leq lta_i \qquad \forall i \qquad (2.13)$$

If a ship of type k does not visit a harbour, decision variable X_{ijk} is 0 and therefore variables A_i and A_j are set to 0 or tt_k^{max} respectively. If the harbours are visited, variables A_i and A_j indicate the arrival times of successive harbours i and j (see Constraints 2.10 and 2.11). Constraint (2.12) sets the departure time for the depot harbour to 0. Constraints (2.13) guarantee that the latest allowed harbour arrival time lta_i is not exceeded.

So far demand could only be picked up at a node or harbour. To be able to also deliver cargo to those nodes, additional pick up and delivery constraints have to be formulated (constraints 2.14 to 2.18).

$$L_{0k} = \sum_i \sum_j d_i \cdot X_{ijk} \qquad \forall k \qquad (2.14)$$
$$L_{jk} \geq L_{0k} - d_j + p_j - m \cdot (1 - X_{0jk}) \qquad \forall j, k \qquad (2.15)$$
$$L_{jk} \geq L_{ik} - d_j + p_j - m \cdot \left(1 - \sum_v X_{ijv}\right) \qquad \forall i, j, k | i \neq j \qquad (2.16)$$
$$L_{0k} \leq q_k \qquad \forall k \qquad (2.17)$$
$$L_{jk} \leq q_k \qquad \forall j, k \qquad (2.18)$$

Constraints (2.14) sum up the cargo on board a ship of type k when reaching its depot or mainland harbour. The cargo on board is allocated to harbours, that are visited after leaving the mainland harbour (depot) and have been picked up at some other island harbours. This is cargo that stays on board a ship when entering the mainland harbour. Constraints (2.15) and (2.16) sum up the cargo, that is unloaded and loaded on board at the mainland harbour or any island harbour respectively. Furthermore capacity constraints (2.17) and (2.18) guarantee that a ship's capacity is not exceeded.

As mentioned above, this pick-up and delivery problem can be transferred from this maritime application to any road based application where only the mode of transportation changes from ships to for example trucks, as far as wheel times are not exceeded.

As an example of a vehicle routing or pick-up and delivery problem with a similar problem to solve for trucks and ships can be found in Nishimura et al. (2009), Aas et al. (2007) or Gribkovskaia et al. (2008). All these decision problems are ship routing problems for feeder services. As mentioned earlier, feeder services operate within a local, mainly short sea environment, delivering cargo (mainly containers) from a hub harbour to spoke harbours and simultaneously picking up cargo at those spoke harbours with the hub harbour or any spoke harbour as destination on the ship's round trip.

Another often found way of operating trains, trucks and aircraft can be transferred to tramp shipping. Here, the typical task is to find an optimal route for delivering a full vehicle load from its pick-up location to its destination. If the capacity is not fully utilized, shippers try to find optional spot cargo that has to be delivered from the same pick-up to the same destination location as the mandatory cargo. After having dropped off this cargo, the shipper is then interested in finding a new order, that has the same pick-up location as the last delivery location or at least a location close to that (as an example see Figure 2.3).

The example in Figure 2.3 shows a possible path of two different ships transporting seven different cargoes between their origin and destination harbour. The cargoes are labeled by their origin and destination harbour. Ship 1's harbour call sequence is A, B, I, D, K, B, E directly starting out with an empty leg from harbours A to B (e.g. without carrying any cargo). Another empty leg is between harbours K and B. Ship 2's harbour calling sequence is F, J, K, E, A, C again with two empty legs between harbours J, K and E, A. This kind of problem can be modelled as a Pick-up and Delivery Problem (PDP) as described by Norstad et al. (2011) and presented in detail in the following for a tramp shipping problem:

Sets and Indices

$i, j \in H$	Set of harbours at which cargoes can be loaded
$i + n \in H$	Corresponding unloading harbour for cargo picked up in harbour i
H_p	Set of pick-up harbours
H_d	Set of delivery harbours
$H_c \subset H_p$	Set of pick-up harbours for mandatory cargo
$H_o \subset H_p$	Set of pick-up harbours for optional cargo
$k \in K$	Set of ship types
$H_k \subset (H_p \cup H_d)$	Cargo at set of Harbours, corresponding to cargo a ship of type k can load

$H_{pk}; H_{dk}$	Set of all pick-up and delivery harbours for cargo a ship of type k can load
$o_k; d_k$	Origin and destination of a ship of type k, either harbour or artificial position at sea

Data

cap_k	Capacity of a ship of type k
qc_i	Weight of cargo from harbour i
$\overline{tw_i}, \underline{tw_i}$	Time interval for each harbour and cargo combination i
s_{ik}	Necessary time to service harbour i by a ship of type k
t_{ijk}	Time for traversing an arc from harbour i to j by a ship of type k
rev_i^h	Revenue for loading cargo from harbour i
c_{ijk}	Cost for traversing an arc from harbour i to j for a ship of type k

Variables

X_{ijk}	1, if a ship of type k is traversing an arc from harbour i to j; 0, otherwise
A_{ik}	Arrival time at harbour i of a ship of type k
L_{jk}	Cargo on board of a ship of type k after leaving harbour j

$$max : \sum_k \sum_{i \in H_k} \sum_{j \in H_k} rev_i^h \cdot X_{ijk} - \sum_k \sum_{i \in H_k} \sum_{j \in H_k} c_{ijk} \cdot X_{ijk} \tag{2.19}$$

The objective function (2.19) maximizes the profit obtained by subtracting all travel dependent costs from the revenue received from transporting cargoes from harbours i to their destination harbour $i + n$.

$$\sum_k \sum_{j \in H_k} X_{ijk} = 1 \qquad \forall i \in H_c \tag{2.20}$$

$$\sum_k \sum_{j \in H_k} X_{ijk} \leq 1 \qquad \forall i \in H_o \tag{2.21}$$

$$\sum_{j \in H_{pk} \bigcup d_k} X_{o_k jk} = 1 \qquad \forall k \tag{2.22}$$

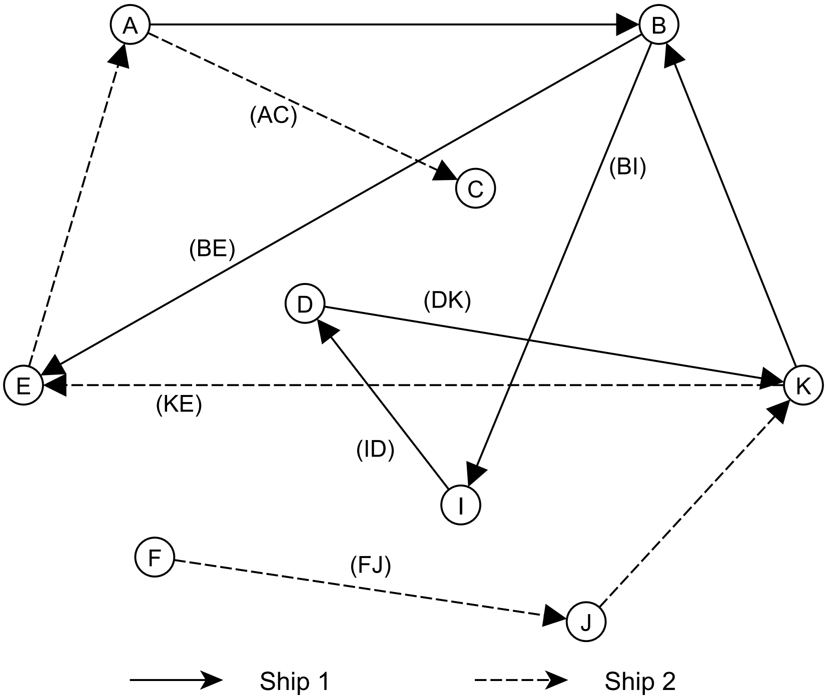

Figure 2.3: Tramp ship routing example, on the basis of Lin and Liu (2011, p. 415)

$$\sum_{i \in H_k} X_{ijk} - \sum_{i \in H_k} X_{jik} = 0 \qquad \forall k, j \in H_k \ \{o_k, d_k\} \quad (2.23)$$

$$\sum_{i \in H_{dk} \bigcup o_k} X_{id_k k} = 1 \qquad \forall k \quad (2.24)$$

$$\sum_{j \in H_k} X_{ijk} - \sum_{j \in H_k} X_{j,i+n,k} = 0 \qquad \forall k, i \in H_{pk} \quad (2.25)$$

$$A_{ik} + s_{ik} + t_{i,i+n,k} - A_{i+n,k} \leq 0 \qquad \forall k, i \in H_{pk} \quad (2.26)$$

$$X_{ijk} \left(A_{ik} + s_{ik} + t_{ijk} - A_{jk} \right) \leq 0 \qquad \forall k, i, j \quad (2.27)$$

$$\underline{tw_i} \leq t_{ik} \leq \overline{tw_i} \qquad \forall k, i \in H_k \quad (2.28)$$

$$X_{ijk} \left(L_{ik} + qc_j - L_{jk} \right) = 0 \qquad \forall k, j \in H_{pk}, (i, j) \in H_k \quad (2.29)$$

$$X_{i,j+n,k} \left(L_{ik} - qc_j - L_{j+n,k} \right) = 0 \quad \forall k, j \in H_{pk}, (i, j+n) \in H_k \quad (2.30)$$

$$L_{o_k k} = 0 \qquad \forall k \quad (2.31)$$

$$\sum_j qc_i X_{ijk} \leq L_{ik} \leq \sum_j cap_k X_{ijk} \qquad \forall k, i \in H_{pk} \quad (2.32)$$

$$0 \leq L_{i+n,k} \leq \sum_j (cap_k - qc_i)\, X_{i+n,j,k} \qquad \forall k, i \in H_{pk} \quad (2.33)$$

$$X_{ijk} \in \{0, 1\} \qquad \forall k, i, j \quad (2.34)$$

Network flow constraints (2.20) to (2.25) are very similar to constraints (2.2) to (2.6) already introduced for the VRP of Karlaftis et al. (2009). Constraints (2.20) guarantee that all mandatory cargo has to be transported and therefore the pick-up harbour has to be visited, whereas constraints (2.21) state that optional spot cargo can also be picked up, but does not have to be transported. The network flow constraints are given in (2.22) to (2.24). Constraints (2.25) ensure that, if a cargo has been picked up in its pick-up harbour, it has to be dropped off at the cargo's corresponding destination harbour. A delivery harbour of a cargo should only be visited if its pick-up harbour has been visited beforehand. This is ensured by constraints (2.26). Constraints (2.27) sum up all travelling and service times of the last harbour visited, to calculate the arrival time at the next harbour. These non-linear formulated constraints can be linearised the same way as done in (2.10) and (2.11) which represent similar constraints. The remaining constraints are loading and time window constraints (2.28) within which a cargo has to be picked up and dropped off. These loading constraints guarantee that cargo is added onto the already present cargo for pick up operations (2.29) and subtracted for unloading operations (2.30). Constraints (2.31) ensure that no cargo is on board a ship of type k at its initial position. The remaining two constraints prior to the binary restrictions of the flow variable (2.34) are capacity constraints ensuring that the total amount of cargo loaded does not exceed the capacity of ships of type k (2.32 and 2.33).

Since trucks, aircraft and trains usually are not able to change their travel speed above a given limit due to physical (aircraft and trains) or governmental restrictions (speed regulations for trucks) or volume of traffic in the same network (trains) the speed as a variable has been removed from the above model. But ships can, except for coastal or harbour regions, change speed in the open sea. This is the reason why Norstad et al. (2011) consider a variable speed setting within a given feasible range, indicated by following additional constraints:

$$\underline{v_k} \leq V_{ijk} \leq \overline{v_k} \qquad \forall k, i, j \qquad (2.35)$$

Here decision variable $V_{ij,k}$ is the speed a ship of type k should travel at when traversing on an arc from a harbour i to a harbour j. This speed is not allowed to be lower than $\underline{v_k}$ and higher than $\overline{v_k}$, the given minimum and maximum speed ships of type k can travel at. Additionally, the costs in the objective function (2.19) are replaced by speed dependent cost $(c_k\left(V_{ijk}\right))$ and are multiplied by the distance (d_{ij}) between two consecutive harbours i and j $(c_k\left(V_{ijk}\right) \cdot d_{ij})$. The multiplication of this term with decision variable X_{ijk} turns objective function (2.19) into a non-linear function. Then t_{ijk}, the time for traversing from harbour i to harbour j with a ship of type k, is replaced by d_{ij}/V_{ijk}, the speed dependent travel time in constraints (2.26) and (2.27).

Characteristic for these types of transportation problems is that the vehicle does not return to a local depot, which can often be found in air, tramp ship and rail road transportation. Often, it is also required for these three transportation modes that cargo is directly transported from its pick-up to its destination harbour without additional stops at nodes or train stations, airports or harbours.

Another way of operation that can occur for land-based, air and water-based transportation is a ferry service. The task for planning a ferry service can be considered as a service network design problem (SDNP). Compared to all other routing and scheduling models introduced so far following example refers to passenger transportation and not to general cargo transportation. This model, formulated as a multicommodity network flow problem, might also be used for general cargo transportation by replacing passengers with general cargo with given demand for each harbour to harbour (or node to node) relation. These node or harbour relations called origin-destination (OD) pairs represent the amount of passengers (cargo) to be transported from an origin node to a destination node with a given point in time a specific demand arrives for service at its origin node. The SDNP has originally been used in the same or similar way as described in the following for other modes of transportation. Yan and Tseng (2002) and Barnhart et al. (2002) adopted the SDNP for an airline routing and scheduling problem where a network is designed in such a way that passenger demands for travelling from one airport to the other is best satisfied by a given aircraft fleet. Another passenger transportation application can be found in Yan and Chen (2002) where the task is to find an inter-city bus network design and timetable setting for buses operating in Taiwan. Two examples with the use of similar model formulations for transporting general cargo are given in Farvolden and Powell (1994) for truck routing and Barnhart and Schneur (1996) for express shipments by air.

The following model has been presented by Lai and Lo (2004). An extension of the same model designing a service network for multiple ferry services operating in and around Hong Kong has been described by Wang and Lo (2008).

Sets and Indices

$d \in R$	Set of origin and destination pairs
N, A	Set of nodes and arcs for the ferry network
$N^b, N^e \subset N$	Set of nodes at the beginning and ending of the planning interval
N_d, A_d	Set of nodes and arcs for the passenger network
S, S_d	Set of service arcs for the ferry and passenger network
W, W_d	Set of waiting arcs for the ferry and passenger network
O_d	Origin arcs of the passenger network
D_d	Destination arcs of the passenger network

Data

cf	Fixed costs for hiring or owning a ferry per day
c_{ij}	Costs for operating a trip between harbours i and j
f	Maximum number of ferries
d_{di}	Passenger demand of origin-destination pair d for harbours $i \in N_d$
cap	Ferry capacity
t_{ij}	Travel time between harbour i and j
tt_d	Travel time of origin destination pair d for direct service
β	Progressing time between two consecutive service arcs
rev_d^c	Revenue for origin destination pair d
wv	Waiting time value
tv	Travel time value
$\overline{u_{ij}}$	Upper bound on ferry flow on arc connecting harbours i and j
$\overline{u_{dij}}$	Upper bound on passenger flow on an arc connecting harbours i and j

Variables

X_{dij}	Passenger flow in a time-space network of origin destination pair d
Y_{ij}	Ferry flow in the ferry time-space network

The set of all arcs A consists of all service arcs S, waiting arcs W, and nodes N. The underlying network is shown in Figure 2.4. Within this ferry network a ferry can either travel on a service arc to the next node or is waiting at the same node (pier) between two time periods. Similar to that the passenger time-space networks $G(N_d, A_d)$ consists of nodes N_d and arcs A_d for each OD pair d. Where A_d again is the joined set of all wait arcs W_d and service arcs S_d.

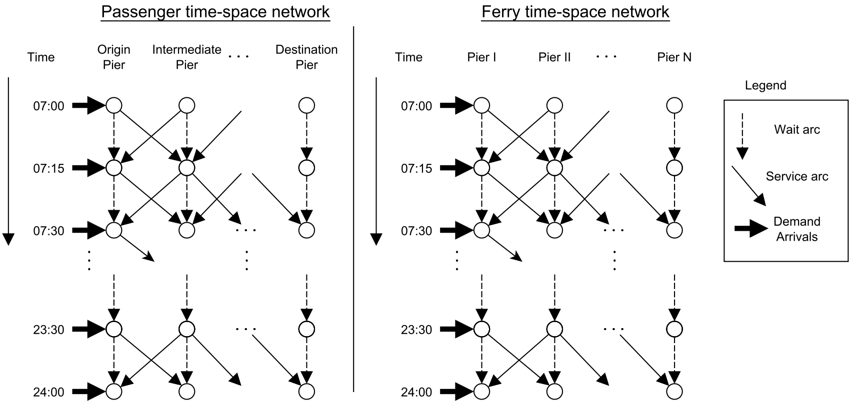

Figure 2.4: Passenger and ferry time-space network, according to Lai and Lo (2004, p. 309, 310)

The objective function (2.36) minimizes the sum of all operating and penalty costs where the first term sums up all fixed costs for owning or hiring a ferry for this planning interval. The second term represents all travel costs for travelling from a node i to a node j. Terms three and four represent all penalty costs which consist of passenger waiting costs and costs for multi-stop trips. A multi-stop trip is less favourable for passengers as the total travel time is increasing with each intermediate stop. Last, all revenue received from offering this transportation service is subtracted.

$$min : \sum_{i \in N^b} \sum_{j \in N \setminus N^b} Y_{ij} \cdot cf + \sum_{i,j \in S} Y_{ij} \cdot c_{ij} +$$
$$\sum_{d} \sum_{i,j \in (W_d, O_d)} X_{dij} \cdot wv \cdot \beta +$$
$$\sum_{d} \left(\sum_{i,j \in S_d} X_{dij} \cdot t_{ij} - X_{dij \in D_d} \cdot tt_d \right) \cdot tv -$$

$$\sum_{d} \sum_{i,j \in D_d} X_{dij} \cdot rev_d^c \tag{2.36}$$

$$\sum_{j \in N} Y_{ij} - \sum_{k \in N} Y_{ki} = 0 \qquad \forall i \in N \setminus \left(N^b \bigcup N^e \right) \tag{2.37}$$

$$\sum_{i \in N^b} \sum_{j \in N \setminus N^b} Y_{ij} \le f \tag{2.38}$$

$$\sum_{j \in N_d} X_{dij} - \sum_{k \in N_d} X_{dki} = d_{di} \qquad \forall i \in N_d, d \tag{2.39}$$

$$\sum_{d} X_{dij} \le Y_{ij} \cdot cap \qquad \forall i, j \in S \tag{2.40}$$

$$0 \le X_{dij} \le \overline{u_{dij}} \qquad \forall i, j \in A_d, O_d, D_d, d \tag{2.41}$$

$$0 \le Y_{ij} \le \overline{u_{ij}} \qquad \forall i, j \in A \tag{2.42}$$

Constraints (2.37) denote the ferry flow conservation constraints stating that every node being visited has to be left again. Constraints (2.38) limit the number of ferries used. Constraints (2.39) are the passenger flow conservation constraints that also indicate at which nodes passengers are entering or leaving the ferry. Capacity constraints (2.40) sum up all passenger flows and guarantees that these do not exceed the ferry's capacity. Last, constraints (2.41) and (2.42) formulate upper and lower bounds for all passenger and ferry flows between nodes i and j respectively.

A SDNP only takes a small time section as a planning interval and tries to match a passenger demand with a given fleet of vehicles. Compared to the later introduced strategic liner shipping service network design problem vehicles do not necessarily return to their original positions and therefore do not perform round trips as needed for the liner shipping service network. But as stated earlier this model formulation very well suits the planning tasks of other modes of transportation.

Literature on truck, train and aircraft routing and scheduling can be found in Cordeau et al. (1998) for rail transportation, Crainic (2003) for long-haul transportation, Crainic and Kim (2007) for intermodal transportation and Crainic (2000) for the above introduces service network design in freight transportation.

2.4 Routing and Scheduling in Maritime Shipping

Extensive literature reviews on ship routing and scheduling are given in Kjeldsen (2009), Christiansen et al. (2004, 2007) and Ronen (1983, 1993). In contrast to truck vehicle routing problems, little work has been done on ship routing and scheduling. Increasing fuel costs and consumer expectations to reduce carbon dioxide and sulphur emission during the transport of products are forcing ship owners and shipping companies not only to minimize costs but also to minimize ship's emissions. In addition, governments are planning to enact the use of even more expensive diesel instead of heavy fuel oil for ocean going ships on their territorial waters. To comply with this framework, vessels are already operated in slow steaming mode for for the purpose of cost and emission reduction purposes. A reduction in speed has significant impact, since vessel fuel consumption has a cubic function in regard to speed.

To show the effect of slow steaming a model for determining emissions as presented by Kranke (2009) can be used. In this model the specific energy consumption at reduced speed (EC_{red}) measured in gram fuel consumed per transported ton and kilometre, is obtained as follows:

$$EC_{red} = EC_{nor} \left(\frac{V_{red}}{V_{nor}}\right)^2 \left[\frac{g}{tkm}\right] \tag{2.43}$$

The energy consumption EC_{nor} for the normal speed is multiplied by the squared fraction of reduced speed V_{red} to the normal speed setting V_{nor}. The CO_2 emission measured in grams CO_2 per transported ton and kilometre results from multiplying the energy consumption with the CO_2-factor (for different CO_2-factors, according to different ship size, see Kranke 2009, p. 38).

$$CO_2\text{-}Emission = EC \cdot (CO_2\text{-}factor) \left[\frac{g_{CO_2}}{tkm}\right] \tag{2.44}$$

As a numerical example a TEU loaded with 14 tons of goods has to be shipped from Hamburg to New York. We will compare the CO_2 emission when travelling at a normal speed of 23 knots with a reduced speed of 18 knots on a 8,000 TEU ship. With an energy consumption of 4.84 [g/tkm] of this ship type at normal speed, the reduced energy consumption results in:

$$EC_{red} = 4.84 \left[\frac{g_{HFO}}{tkm}\right] \cdot \left(\frac{18kn}{23kn}\right)^2 = 2.96 \left[\frac{g}{tkm}\right] \tag{2.45}$$

For a distance of 6,526 kilometres (3,524 nm) between Hamburg and New York the amount of CO_2 emitted in kg at a speed of 23 knots and a CO_2-factor of 3.114 grams CO_2 per gram heavy fuel oil (HFO) sums up to:

$$CO_2\text{-}Emission_{23kn} = 4.84 \left[\frac{g_{HFO}}{tkm}\right] \cdot 3.114 \left[\frac{g_{CO_2}}{g_{HFO}}\right] = 15.07 \left[\frac{g_{CO_2}}{tkm}\right] \quad (2.46)$$

$$\Rightarrow 15.07 \left[\frac{g_{CO_2}}{tkm}\right] \cdot 14\,[t] \cdot 6,526\,[km] = 1,376.9\,[kg] \quad (2.47)$$

and at 18 knots:

$$CO_2\text{-}Emission_{18kn} = 2.96 \left[\frac{g_{HFO}}{tkm}\right] \cdot 3.114 \left[\frac{g_{CO_2}}{g_{HFO}}\right] = 9.22 \left[\frac{g_{CO_2}}{tkm}\right] \quad (2.48)$$

$$\Rightarrow 9.22 \left[\frac{g_{CO_2}}{tkm}\right] \cdot 14\,[t] \cdot 6,526\,[km] = 842.4\,[kg] \quad (2.49)$$

The speed reduction of 28% results in a CO_2 reduction of 63%.

Most likely ship owners will only operate their fleets in slow steam mode, as long as its profitability increases. A paper presented by Cariou (2011) states that emissions have been reduced by 11% from 2009 to 2010 and that the bunker break-even price of at least 259$ per ton IFO will not lead to a situation where carriers return to normal speed in the near future. The break-even price indicates the price of bunker fuel, from which on slow steaming is beneficial for a ship, operating at a given cargo rate and demand. With a current bunker fuel price of over 600$ for IFO380 at Rotterdam harbour (Bunkerworld 2011) and steadily increasing, even more ship operators will restrain from returning to normal speed. Note, for specific trade routes on which the berthing times are high in regard to voyage times (e.g. Australia / Oceania and Latin America / Caribbean) the break-even-point is 568$ and 556$ respectively and in this case slow steaming might not lead to profit maximization if bunker prices slightly fall.

To meet their schedules, a lot of effort has been put into reducing ship's demurrage time in harbours. The increase of the maximum permitted harbour to harbour travel time allows cruising with reduced speed. An articles concerning the reduction of demurrage can be found in (Christiansen et al. 2004, p. 12). The approach concentrated on in this thesis uses alternative vessel propulsion modes to reduce costs and emissions of a whole fleet in a supply network. In the following a selection of the most recent research about the field of ship routing and scheduling will be presented. Note, the focus will lie on the water side planning tasks.

2.4.1 Examples of Operational and Tactical Planning

Operational Planning

Considerable research has been done on ship routing and scheduling under an operational perspective by optimizing the efficiency of harbour to harbour routing. In short sea shipping the aim is to minimize the travel distance and estimate the time of arrival by circumnavigating coastlines or shallow waters (Fagerholt et al. 2000). Further literature close to our operational, environmental shortest path problem are given in Section 3.1 (see Page 40).

Another operational planning task is to prevent a ship from stability problems, by planning the container stowage accordingly. Examples of container stowage planning tasks can be found in Wilson and Roach (2000) and Kang and Kim (2002).

In cases of overbooking or a no-show of accepted cargo, shipping companies have to decide which containers to load and if capacity is exceeded, which cargo to book on later ships. This problem is addressed in Ang et al. (2007). Their multi-period sea cargo mix problem is solved with heuristic algorithms providing fast and nearly optimal solutions for this time critical operational planning problem. Based on surcharges, higher or lower prices and costs, the most profitable cargo is transported and others rejected.

Tactical Planning

An example of a tactical planning problem in maritime transportation with the objective of minimizing fuel emissions by optimizing speed on shipping routes, is given by Fagerholt et al. (2010). This problem can be used in a tramp- or industrial shipping setting, where a certain amount of cargo orders is known at specific harbours for the near future and have to be planned in such a way that fuel emissions are reduced by optimizing the speed on each harbour-to-harbour relation and simultaneously satisfying the harbours time windows. In this case the time windows might depend on the earliest pick-up time of a cargo at its loading harbour and its latest arrival time at its unloading harbour. Environmental influences such as wind, waves and currents are not accounted for. Significant savings of fuel (24.3%) and emissions (19.4%) can be achieved by the described shortest path approaches with different optimized average speed settings on each harbour-to-harbour realtion, instead of travelling with the same constant speed on all harbour relations.

An inventory routing problem, also classified as a tactical planning problem, is presented by Grønhaug et al. (2010) who solve the problem by use of a branch-and-price method. Branch-and-price methods use a branch-and-bound algorithm, where upper bounds are calculated by a column generation technique. This inventory routing problem, that we will present in detail, has been designed for a company transporting liquefied natural gas (LNG). In this industrial shipping context, the task is to prevent an out-of-stock situation at consumption harbours, where the LNG is regasified to natural gas (NG). Additionally, the LNG storage capacity at harbours where the NG is cooled down in the liquefaction plants, shall also not be exceeded. LNG tankers now have to be scheduled in a way that all constraints are fulfilled. In their mathematical model formulation binary variables Λ_{kr} represent the columns of the column generation approach, which have value 1 if a ship of type k is travelling on route r, or 0 otherwise. The design of routes is part of the branch-and-price's subproblem which will not be presented here in detail.

Sets and Indices

N^P	Set of pick-up harbours, liquefaction plants
N^D	Set of delivery harbours, regasification terminals
$k \in K$	Set of ship types
$i, j \in N = N^P \cup N^D$	Set of harbours
$r \in R_k$	Set of routes for ships of type k
$t \in T$	Set of time periods

Data

s_{it}^{LNG}	Lower bound on sales of LNG in harbour i and time period t
p_{it}	Upper bound on production of LNG in harbour i and time period t
rev_{it}^{g}	Revenue obtained from transporting and selling gas in harbour i and time period t
cp_{it}	Costs for producing LNG in harbour i and time period t
$\overline{inv_i}$	Upper bound on inventory level of LNG in harbour i
$\underline{inv_i}$	Lower bound on inventory level of LNG in harbour i
h_i	Harbour visiting indicator has value +1 for delivery harbours and -1 for pick-up harbours i
x_{ijktr}	1, if a ship of type k (un-)loads at harbour i in t before travelling to harbour j on route r; 0, otherwise
z_{iktr}	1, if ship k visits harbour i in t on route r; 0, otherwise
q_{iktr}	(Un-)Loading volume at harbour i by a ship of type k in time period t on route r
l_{iktr}	Number of tanks unloaded from ship of type k at harbour i in t on route r
w_k	Number of tanks on ship k
ct_{kr}	Costs for a ship of type k travelling on route r
$ncap_i$	Number of ships that can unload simultaneously in harbour i
$tcap_k$	Maximum number of tanks in ship of type k

Variables

Y_{it}	Sales or production of LNG in harbour i in time period t
S_{it}	Inventory level of storage in harbour i in time period t
Λ_{kr}	Number of round trips a ship of type k makes on its assigned route r during one planning interval

$$max: \sum_{i\in N^D}\sum_t rev_{it}^g \cdot Y_{it} - \sum_{i\in N^P}\sum_t cp_{it}\cdot Y_{it} - \sum_k\sum_r ct_{kr}\Lambda_{kr} \quad (2.50)$$

The objective function (2.50) maximizes the profit obtained from revenues subtracted by production and transportation costs and is subject to following constraints:

$$S_{it} - S_{i,t-1} - \sum_k\sum_r h_i\cdot q_{iktr}\Lambda_{kr} + h_i\cdot Y_{it} = 0 \qquad \forall i,t \quad (2.51)$$

$$\sum_k\sum_r z_{iktr}\cdot\Lambda_{kr} \leq ncap_i \qquad \forall i,t \quad (2.52)$$

$$\underline{inv_i} \leq S_{it} \leq \overline{inv_i} \qquad \forall i,t \quad (2.53)$$

$$s_{it}^{LNG} \leq Y_{it} \leq p_{it} \qquad \forall i,t \quad (2.54)$$

$$\sum_r \Lambda_{kr} = 1 \qquad \forall k \quad (2.55)$$

$$\sum_r l_{iktr}\cdot\Lambda_{kr} \leq tcap_k \qquad \forall i\in N^D, k, t \quad (2.56)$$

$$\sum_r x_{ijktr}\cdot\Lambda_{kr} \leq 1 \qquad \forall i,j,k,t \quad (2.57)$$

Constraints (2.51) guarantee that inventory capacity in the pick-up and delivery harbours is neither exceeded nor that an out of stock situation occurs. The berth capacity constraints (2.52) prevent that an upper bound of maximum allowed ships in the harbour for unloading or loading activities is surpassed. The amount of LNG stored (see constraints 2.53) and the amount of LNG produced (see constraints 2.54) has to stay within a given interval. Convexity constraints (2.55) assure that each ship type is assigned to only one route. For each ship type k the number of cargo tanks unloaded in delivery harbours i must be smaller than the maximum number of tanks on the ship (see constraints 2.56). Constraints (2.57) indicate in which time period t a ship of type k is visiting harbour j after having visited harbour i on route r.

Another inventory routing problem with the aim of transferring liquid bulk products from production harbours to consumption harbours is presented in Al-Khayyal and Hwang (2007). The mixed integer model approach minimizes all costs for ships with different compartments, capable of transporting different product types. A very similar mixed integer programming approach, which additionally takes into consideration the blending of grain products is shown in Bilgen and Ozkarahan (2007).

Two examples for the tramp shipping industry transporting bulk cargo are the ones described by Brønmo et al. (2007) and Korsvik et al. (2010). Both consider additional optional spot cargo that can be transported on top of a mandatory given order. The mandatory bulk cargo has to be transported due to long-term contracts, whereas spot cargo will only be transported if this is profitable under given ship's capacity and harbour entering constraints. To solve models, Brønmo et al. (2007) use a multi-start local search heuristic, whereas Korsvik et al. (2010) are able to show that their tabu search heuristic performs even better than that of Brønmo et al. (2007), which has been tested for 13 real data case instances. The decision on whether or not to transport optional spot cargo is very time sensitive. Therefore heuristics are used to find good feasible solutions and to uphold a short response time.

Korsvik et al. (2011) improved their last mentioned approach by allowing split loads and stochastic demand. Again, mandatory bulk cargo has to be loaded and optional spot cargo can be transported additionally on the remaining unused capacities. They propose a large neighbourhood search heuristic for solving this problem. With this extension they were able to show that a better utilisation a ship's capacity has a significant impact on the revenue generated. With a rise in fuel price the beneficial effect is even larger.

A very similar problem is also described by Lin and Liu (2011). They use a genetic solution approach to simultaneously solve a ship allocation, freight assignment and ship routing problem in a tramp shipping environment. Compared to Korsvik et al. (2011) they do not allow for split loads and also do not account for stochastic demand.

Another tramp ship routing and scheduling problem considering variable speed settings on arcs between two successive harbours is subject to research from Norstad et al. (2011). Within given time windows for loading and unloading specific cargoes, the variable speed arrangement allows for additional spot cargo to be shipped. That way revenue is increased compared to fixed speed settings where this additional spot cargo might not have been transported due to the given time window constraints. Furthermore, even with a typical cubic function of fuel consumption and likewise rising costs with increasing speed, higher costs due to only partly raised speed do not exceed the revenue gain from variable speeds. This model is presented in Section 2.3 (see Page 20) without the speed selection as a typical tramp shipping or truck and aircraft routing problem.

A combined Fleet Size & Mix Problem and Fleet Deployment Problem for a liner shipping network design and cargo booking task has been stated by Meng and Wang (2010). They call their problem a short-term Liner Ship Fleet Planning Problem where the shipment of forecasted cargo demand has to be satisfied by a given liner service schedule. The objective is to minimize the total operating costs by varying the fleet size and mix (amount and type of ships used) at a given harbour visiting frequency. The main task of this model is to consider an uncertain cargo demand distribution while maintaining a promised service level. This problem has been solved as a chance constraint mixed integer programming model.

Another paper on the Fleet Size & Mix Problem by Meng and Wang (2011) states that ships should only be chartered on a short-term basis. For a long-term planning horizon it is cheaper to purchase ships. Their multi-period liner ship fleet planning problem (MPLSFP) under given deterministic container shipment demand has been modelled as a scenario-based dynamic programming approach and can be solved by any shortest path algorithm.

2.4.2 Examples of Strategic Planning

Several articles are covering the problem of optimizing the schedule of a ship fleet within a given supply chain which is according to Christiansen et al. (2007, see Pages 201, 220) a strategic planning task. Appelgren (1969) is the first to describe a problem that solves the optimal sequence of cargoes each ship of a fleet should transport under given time limits.

Ronen (1986) defines the minimal fleet operating costs under storage and handling constraints at the harbours.

A further aspect being considered in a supply chain including maritime transportation can again be the inventory in harbours of the described supply chain. Christiansen (1999) presents a mixed integer programming model for optimizing a pick-up and delivery problem under inventory and time constraints in a supply chain, when ammonia has to be transported by ships between production and consumption harbours. These inventory routing problems can also be modelled with variable vessel speed by set partitioning (e.g. Brown et al. 1987).

Similar to Brown et al., Fisher and Rosenwein (1989) solve the selection problem of alternative operating speed by the use of a different set partitioning approach.

Papadakis and Perakis (1990) even show a method for finding the optimal speed selection in a ship routing pick-up and delivery problem.

Brown et al. (2007) describe a problem, where different operating modes for navy vessels save up to 12.5% of fuel by only varying the engine setting.

In many cases liner shipping network design as a strategic planning problem deals with the question, whether to have a fleet of ships travelling at a lower speed but with the need of more ships or, travelling at a higher speed and therefore using fewer ships. To show the influence of the selected average fleet speed on the fleet size an example calculation is introduced. V is the average speed of the fleet when travelling on a liner service round trip. N_S is the number of ships needed to uphold a promised visiting frequency F (e.g. once a week) at all harbours. N_H is the number of visited harbours and T_H is the average time spent in a harbour for loading and unloading activities. Δ accounts for the total travelled distance of one round trip.

$$N_S \geq \left(N_H \cdot T_H + \frac{\Delta}{V} \right) \cdot F \tag{2.58}$$

For an example following values are assumed: $V = 22$ kn; $F = 1/168$; $N_H = 13$; $T_H = 22h$; $\Delta = 23,276nm$. Using formula (2.58) given by Notteboom and Vernimmen (2009), we receive $N_S = 8$ for a speed of $22kn$. Reducing the speed to $19kn$ leads to $N_S \geq 8.99$. As a result at least one more ship is needed to maintain the same service at a reduced speed.

A similar planning task has been addressed by Ronen (2011). He finds, that when considering fuel costs, it is beneficial to operate ships within a container liner shipping environment at their minimal-cost speed for the resulting amount of ships needed to guarantee a given harbour visiting frequency. The optimal selection of speed combined with the number of vessels needed to perform a permanent route round trip at minimum costs, is addressed in Chapter 4.

The problem of assigning limited container carrying capacity to different carriers within an alliance has been addressed by Agarwal and Ergun (2010). They use an allocation mechanism which combines mathematical programming and game theory in order to find the optimal collaboration strategy. Every carrier who's aim is to maximize his own profits, is encouraged in efficiently participating in this alliance by incentive side payments.

A model that analyses the influence of ship sizes on the total transport cost of a standard container within an intermodal transportation system is shown by Schönknecht (2007). He finds out, that the use of Super-Post-Panamax ships, with a capacity of up to 14,000 TEU, will reduce transportation costs of containers. But with increasing size, ships are limited to only a few harbours that they can call at. Due to their container holding capacity, more containers have to be loaded and unloaded in harbours, which also leads to longer berthing times.

A simulation based optimisation approach in an intermodal freight transportation environment which investigates the fleet size and mix container liner shipping decisions, has been presented by Dong and Song (2012). They analyse the influence of hinterland transportation times and its uncertainty on the optimal fleet size of container liner services.

A service network design and a combined asset management problem solved with a branch-and-price algorithm, has been presented by **?**. Their master problem solves the multicommodity network design problem under given vehicle management constraints. The column-generation based problem branches into two additional subproblems. One subproblem generates the vehicle dependent cycles and the other subproblem generates the path-flows for each cargo transported. This model is not only applicable to maritime transportation, but has also been tested on real-life based rail transportation case instances.

The question whether to design multi-harbour or hub & spoke networks for container ship liner services has been studied by Imai et al. (2009). A multi-harbour network is a round trip of a liner service with multiple harbours to be called at, whereas in a hub & spoke network configuration, larger ships operate between major transshipment hubs from where smaller feeder ships service local harbours in a spoke network. Imai et al. (2009) choose a two stage approach with the first step being the service network design and the second step being the container distribution across the liner service. The result of their research is, that even when considering mega-containerships with a capacity of more than 20,000 TEU, multi-harbour networks are more beneficial than hub & spoke networks, when empty container repositioning is a vital part of the underlying problem.

Literature on the strategic planning tasks for liner services will also be partly discussed in Chapter 4.

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A Liner Shipping Network Design
Routing and Scheduling Considering Environmental Influences
Windeck, V.
2013, XXVI, 136 p. 43 illus., Softcover
ISBN: 978-3-658-00698-3