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A Review of Maritime Operations

Maritime transportation is the least costly mode of transportation and, as such, it plays a major role in the world trade expansions. This chapter provides an overview of the importance of maritime transportation in current global economic conditions (section 1.1) and introduces various types of loads and ships in maritime transportation (section 1.2). Containerization, a revolutionary concept in maritime transportation, is reviewed in section 1.3, followed by a brief introduction to handling equipment in seaports in section 1.4. A short overview of the main optimization problems faced in maritime operations is presented in section 1.5 and the chapter is concluded in section 1.6.

1.1. Maritime transportation

Nowadays, supply chain networks are increasingly complex, and the logistics associated with them present more challenges than ever, mainly due to the fast trend of globalization. The ever-increasing importance of sustainable development strongly depends on the development of transportation infrastructures. Although there is no explicit hint to transportation in the United Nations' sustainable development goals [UNI 18], it is considered as the most critical factor to reach its goals and targets.

As an essential tool, maritime transportation lies at the heart of globalization and the international trade boom. This mode of transportation revolutionized industries by enabling almost any company, regardless of its size and location, to export its products all around the world. Maritime transportation, mainly ocean and deep sea, is considered as the corridor of global international trade. Conceptually, any goods, other than time- or content-sensitive ones, can be moved by sea. Although maritime transportation is one of the slowest modes of transportation, due to its higher transported volumes and lower operational costs, it is a widely used intercontinental transportation mode for all types of loads, from heavy loads such as ores, grains, coal and coke, to liquid loads such as crude oil and liquefied natural gas, and to final products such as cars, digital instruments and household appliances. If the delivery time is not an important matter, larger, odd-shaped products including engines and propellers may be moved via this mode, as well. Many types of cargo can only be transported by sea since, due to either their size or shape, there is no other physically or economically viable option.

According to Yuan [YUA 16], almost 85% of total international trade is transported by sea. More specifically, for the EU member states, 75% of their imports and exports depend on maritime transport [EUR 15]. It is the leading mode of long-distance transportation in the world, with a transported volume of over 10.6 billion tons in early 2017, almost twice that of 1995. Although this increase represents an annual average growth of almost 3.5% in the past 22 years, a similar and steady annual growth is expected in the near future, approximately 3.2% during 2017 to 2022 to reach 12.5 billion tons of transportation by 2022 [UNC 17].

The fast increase in the worldwide fleet size and fleet capacity, consisting now of more than 93,000 commercial ships with a total tonnage of 1.86 billion deadweight tons (DWT), has been a key factor in globalization and lies at the center of global support supply chains. Massive transportation capacity, as well as low carrying costs, has led most countries to increase the throughput of their maritime transportation, especially developing countries, which by 2016 accounted for around 59 percent of loaded (i.e. exports) and 64 percent of unloaded (i.e. imports) total volumes of international maritime trade [UNC 17].

Although maritime transportation has almost the longest transit time and needs the highest level of capital investments, it is known as the least expensive and safest mode of long-distance transportation. Additionally, while the size and weight are an important issue for air transportation, this is not the case for maritime transportation. Although ships usually need to travel a longer distance compared with other modes of transportation, maritime transportation is still the mode with the least CO_2 emissions.

Nevertheless, the maritime industry itself is seriously affected by the impacts of climate change, such as rising sea levels and more extreme weather [VIL 15].

To compare different modes of transportation, we selected a very common route between Shanghai in China (busiest container terminal in the world), and Rotterdam in the Netherlands (busiest container terminal in Europe). To have a fair comparison, we estimated that one twenty-foot equivalent unit (TEU) container, a common unit to count carrying capacity by train, trucks and ships, is able to carry 20 tons of load, on average. Table 1.1 shows an estimation of the average transportation costs for one TEU by a ship or a train and 20 tons of load by plane or trucks. The data presented in this table have been gathered through surveying duration, distance and cost from [SEA 18, CAR 18, UNC 17], and emission rates from [HIL 18]. The emission rate is counted by grams of CO_2 per ton-kilometer (g/tkm). Although maritime transportation is the longest mode of transportation, it is the cheapest and greenest mode of transportation, as well. It is noteworthy that air cargo produces almost 100 times more CO_2 than maritime transportation.

Mode of transportation	Duration	Distance	Emission rate (CO_2)	Emission for a 20-ton load	Cost
Air	1–10 days	9,000 Km	1278 g/tkm	230 tons	50,000 $ for 20 tons
Road	10–15 days	11,000 Km	59.8 g/tkm	13.1 tons	8,300 $ for 20 tons
Rail	18–25 days	11,000 Km	22.6 g/tkm	4.9 tons	3,000 $ per TEU
Sea	32–43 days	19,000 Km	5.6 g/tkm	2.2 tons	700 $ per TEU

Table 1.1. *Comparison between the four main modes of transportation in a route between Shanghai and Rotterdam*

1.2. Types of ships and cargo

Bulk cargo is mainly divided into four categories, dry bulk cargo (e.g. grains, sand, coal, ores, etc.), liquid cargo (e.g. crude oil, LNG, liquid fuels, chemicals, vegetable oil, etc.), other main bulk commodities or break bulk (e.g. goods in sacks, cartons, crates, wood, paper, steel, autos), and containers. These four main cargo categories have a certain portion of the maritime transportation market, depicted in Figure 1.1, based on the data from [UNC 17] for the year 2016.

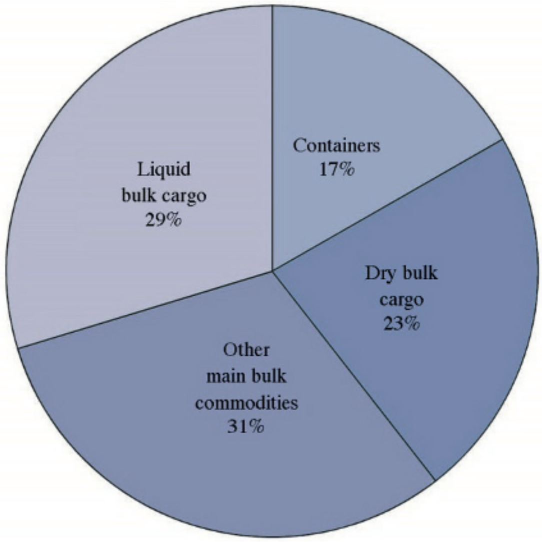

Figure 1.1. *Market share of cargos transported by sea in 2016*

There are currently three main routes in the world for maritime container transportations, namely from Asia to Europe, from Asia to North America and from Europe to North America [GEL 13]. Main routes for oil and gas include the Persian Gulf to Asia, Europe and North America. For the dry bulk cargo (mainly iron ore and coal), the main routes are from Latin America to Europe and to the Far East, and from Australia to the Far East. Other commodities are transported all over the world, but mainly from the Far East to Europe and to North America. Cargo flows are set to expand across all segments, with containerized and dry bulk cargo trades recording the fastest growth.

Beside leisure, educational and passenger ships, most of the larger ships are used for merchant purposes. The smallest portion of the world fleet belongs to the Ferries and passenger ships with less than 0.3% of the total tonnage.

Huge tanker ships transport fluids such as crude oil, petroleum products, liquefied petroleum gas (LPG), liquefied natural gas (LNG) and chemicals, also vegetable oils, wine and other foods. Currently, tankers have more than 500 million tones of DWT accounting for 28.7% of the world commercial fleet deadweight [UNC 17]. However, the largest portion of the commercial fleet is dedicated to the dry bulk cargo ship with almost 800 million tones of DWT, which represents 42.8% of the world fleet deadweight. Break-bulk cargo ships represent just under 4% of the world fleet deadweight. A special version of the break bulk cargo ships, known as roll-on/roll-off (RORO), are used to carry wheeled cargo such as automobiles, trailers or railway carriages. RORO ships have built-in ramps that allow the cargo to be efficiently "rolled on" and "rolled off" from the ship when in port. Perishable goods such as fruits, meat, fish, vegetables and dairy products, which need temperature-controlled transportation, are transported in refrigerated ships (reefers).

The most preferred mode of transportation for containers is the containerships, which, with 245 million tons of DWT, account for 13.2% of the world fleet DWT. They are, typically, operated on fixed maritime routes that include various container terminals worldwide. For the deep-sea containerships with a general capacity of several thousand TEUs, the deck is subdivided into several holds, each of which can carry between 200 to 400 containers. Containers may be stacked on the deck or below deck. Deep sea containerships are mainly used for interlinking Europe, North America, South America, the Far East and the Middle East. For the shorter distances between the countries or intra-continent, short-sea containerships with a capacity of several hundred TEUs are in service. Feeders and Barges are two other types of ships for carrying containers. The former carries up to several hundred TEUs to/from deep-sea ships, and the latter is a small size ship with a capacity of dozens of TEUs that serve the hinterland of a seaport via rivers and channels.

1.3. Containerization

A shipping container is a box designed to enable goods to be delivered from door to door without its contents being physically handled [CHE 05]. In the last 60 years, containerization has revolutionized maritime transportation by making it much more cost-effective. A major part of today's maritime transportation is performed using containers. Although the first ship built to carry containers dates back to 1926 (four containers were used to carry passenger luggage in a regular luxury connection between London and Paris), regular sea container service between the US East Coast and points in the Caribbean, Central and South America started in 1961. The standard dimensions of containers are 8 feet wide, 8.6 feet high and either 20 or 40 feet long. However, other lengths can still be found, namely eight, ten and thirty feet. A 20-feet-long empty container weighs approximately 2.2 tons and it can be loaded with up to 22.7 tons [KEN 13].

Standardization of these metal boxes allowed for easier loading and unloading processes, the design of standard handling equipment, protection against weather and theft, and scheduling and controlling in seaports. The aforementioned advantages resulted in a larger physical flow of cargo and an increased acceptability of the containers, which led to higher profitability. It is important to note that ships are productive only when sailing. Currently, on average the general cargo ships spend 50–70% of their time in ports to be loaded and/ or unloaded; while containerships spend only 15–30%, making them more profitable [CHR 13].

Container terminals (CTs) are an area in the seaports, where containerships dock on a berth to be loaded or unloaded [VAC 07]. The goal of the CT is to move the containers as quickly as possible and at the lowest possible cost. Therefore, it is essential for a CT to be able to efficiently and rapidly receive, store and dispatch containers. The ever-increasing demand for containerized transportation has compelled ports to improve their facilities. This is one way of developing economies to benefit from greater connectivity to world markets, improve trade and lower their transport costs. These countries have many plans to construct new CTs or to increase the capacity of existing ones. The economy of developing countries is highly dependent on the extension of their loading/unloading capacity of containers, concurrent to their cargo fleet; however, future improvements and investments in facilities and operating knowledge highly depend on global economic conditions. The growth rate in developing countries varies over the years due to strong fluctuations in trade and a need to improve reports and a lack of data.

The world fleet continues to expand; by mid-2017, there were 11,150 containerships with a total capacity of 22.3 million TEUs. Germany holds a predominant first place followed by China, Greece, Denmark and Hong Kong, which together hold 52.1 percent of the market share. Overcapacity and poor market conditions are the two most important challenges for both the container terminal operators and the containership owners. However, the latest reliable statistics for 2016 published by [UNC 17] indicate that 699.7 million TEUs have been moved through container ports all over the world. This is more than three times the 231.7 million TEUs moved during 2000. It seems that container transportation has achieved its potential market share, since most of the suitable cargos are already containerized; thus, the future growth of containerization will mainly be due to global trade growth. Figure 1.2 shows the top twenty CTs in the world, which collectively accounted for 45.2 percent of the world container terminal traffic in 2016. The ports are sorted based on their throughput in 2016, according to data gathered from [UNC 17].

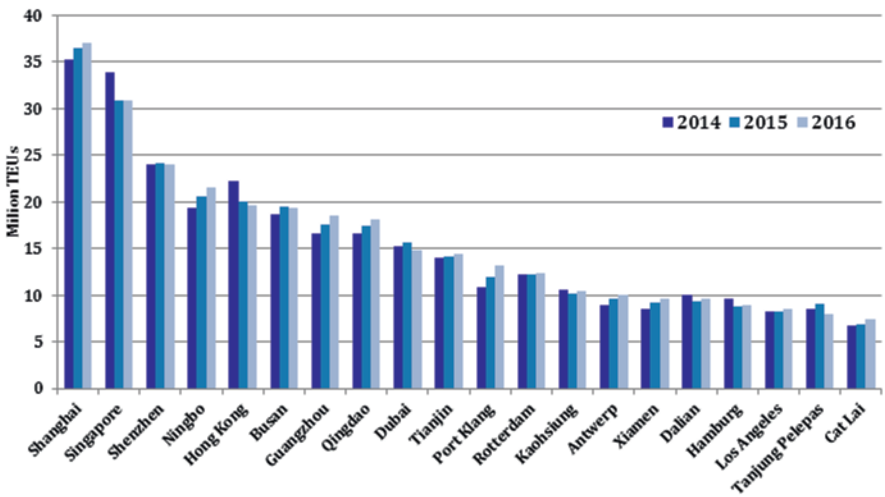

Figure 1.2. *Annual throughput (million TEUs) of top twenty CTs in the world ranked as of 2016*

Huge maritime ships transfer containers between the continents. The size of these ships has increased enormously, e.g. the nominal capacity of the largest containership in service is 19,224 TEUs [UNC 17], and the next generation of containerships are conceptually designed for 22,800 to 24,000 TEUs [LIN 17a]. These much larger containerships demand a quicker turnaround of ships and thus, CTs have to resort to new techniques and technologies to coordinate all types of handling equipment, leading to more efficient container terminals. Therefore, it forces changes such as the replacement of manually operated cranes by automated cranes and manually driven carts by automated guided vehicles (AGVs), among others.

Automation of handling equipment in CTs is a response to the ever-increasing container traffic. Automated container terminals are fully automated terminals, which integrate automated storage yard, AGVs and quay cranes. This is a general solution for the increasing demand for CT throughput. Researchers have introduced automated container terminals to reduce operational costs, especially labor costs, and to increase the throughput of the CTs. Although initial investment for automated container terminals is definitely higher than this for traditional CTs, the operational costs of automated container terminals are less than those of traditional CTs. Thus, being able to pay for the investment in a shorter period of time.

Euromax CT in Rotterdam, Netherlands, Altenwerder CT in Hamburg, Germany, New Qianwan CT in Qingdao, China, Victoria international CT in Melbourne, Australia, the Pasir Panjang terminal in Singapore and the Kawasaki Port in Japan are examples of container terminals that are partially automated with plans for full automation in the short term.

1.4. Handling equipment in seaports

A seaport can be defined as a facility situated at the edge of an ocean or sea for receiving ships and transferring cargo to and from them. A seaport is further categorized as a “cruise port” or a “cargo port”. Sea cargo ports serve containerships (see Figure 1.3 for a top view of the CTs), tankers, dry bulk carriers and other general cargo. The port of Shanghai in China is the largest and busiest port in the world regarding cargo tonnage, followed by the ports of Singapore and Hong Kong; while the busiest in Europe is the Port of Rotterdam, Netherlands.

Seaports primarily serve as an interface between different modes of transportation, e.g. domestic rail, truck transportation or deep sea maritime transport. In seaports, a ship moors at a berth and waits to be loaded or unloaded. It is common practice to dedicate a part of the seaports (known as a terminal) to a specific type of load (i.e. for dry and liquid bulks, or for containers). Although various types of loads need different types of equipment in a seaport, generally similar activities are performed to load/unload a ship. The exporting loads are received from the hinterland through the terminal gate. After the initial legal inspections, they are transferred to the storage yard waiting for the expected arrival time of a ship. After its arrival, the load is retrieved from the storage yards being transferred to a crane or loader to be loaded into the ship. The importing loads (unloading from a ship) go through the same process but in a reverse mode;

that is, the load needs to be transferred to the storage area, from where it will be delivered to the final customer or to another mode of transportation (e.g. trains, smaller ships, or trucks). Commonly, the unloading process of a ship precedes its loading process.

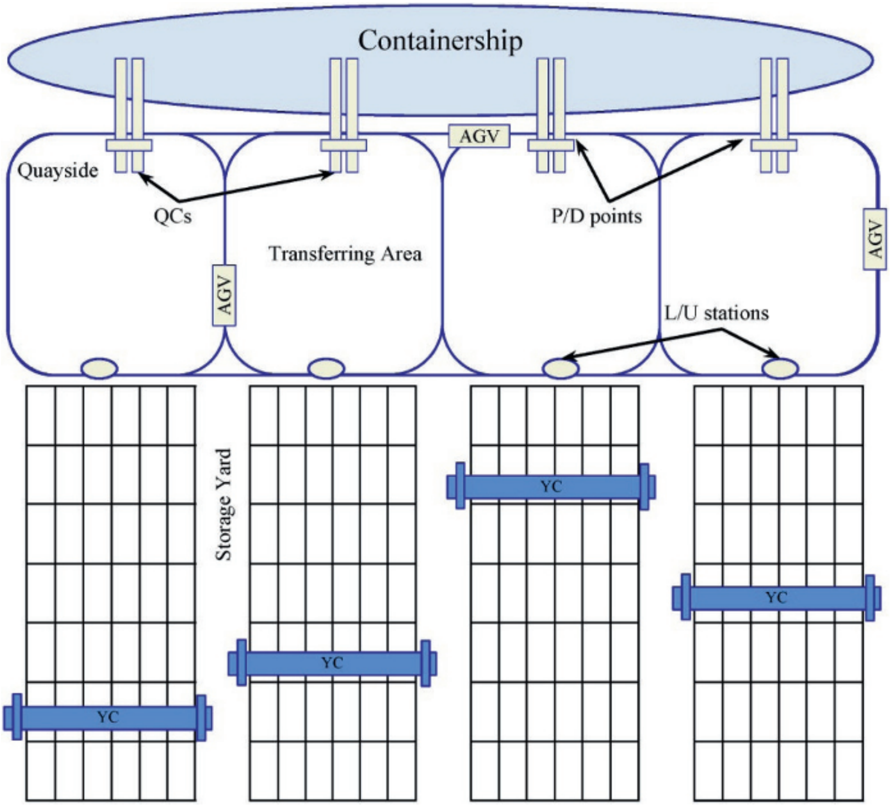

Figure 1.3. *A top view of the container terminal*

The third type of load is the transshipment one (quite common with containers), in which containers are unloaded from a ship, stored temporarily in the yard and then loaded to another ship. More specifically, some of the large container terminals in the world are known as hubs for transshipment containers. For example, 80% of the handled containers in Pasir Panjang terminal in Singapore, the largest hub in the world, are transshipment, while 70–80% of the containers are either imported from or exported to the largest European port in Rotterdam, Netherlands [KEN 13].

A seaport can theoretically be divided into five main areas: berth, quay, transferring area, storage yard and terminal gate. Usually, the berth and quay areas are known as the seaside, and the transferring area, the storage yard and the terminal gate are known as yard side. In this book, we concentrate on the optimization problems related to the ships, seaside and yard side operations except the ones associated with delivering loads to other modes of transportation or final customers. The next sections introduce some special handling equipment used in seaports.

1.4.1. *Quay cranes*

The aforementioned four types of loads need specific types of cranes to be loaded and/or unloaded to and/or from the ships. Liquid bulk cargo is usually pumped through the pipelines from and/or to the storage tanks, and then distributed to the other modes of transportation. Dangerous materials are commonly handled at special berths constructed for such a purpose, usually not too far from the main berth area of the seaport.

Dry bulk cargos are divided into two main categories, namely: major bulks and minor bulks; the former representing about two-thirds of the dry bulk trade. Major bulk deals include ore, coal and grains; while minor bulks include several goods such as steel, forest and agricultural products, fertilizers, and cement, among others. The handling equipment needed differs depending on the good being handled and may include loading shovels, bulldozers, clamshell grabs, hoppers, suction pipes, and conveyor belts. Common to all of them is the fact that their loading and/or unloading are highly mechanized, requiring very few people to be involved.

Break-bulk cargo refers to goods that must be handled individually, which is usually done by a floating crane either installed on the ship itself, or in the quayside. Goods are fitted in containers, boxes or bags, which are then placed in pallets. The pallets and/or containers are fitted with lifting slings and then lifted, usually in groups, to be loaded to or unloaded from the ship. Most of the preparation for lifting is done by manual labor, which is the main reason for the large costs associated with handling this type of cargo.

Container cargo refers to the transport of containers, regardless of their contents, usually truck-size intermodal containers. Since containers are large and heavy, specialized material handling equipment is required for transporting them within the terminal. Most of the types of handling equipment are able to carry only one container at the time, and there are limitations to how far they can carry a container. Containerships dock on a berth and containers are loaded and unloaded using huge cranes, typically rail-mounted, quay cranes (QC) or container cranes. The QCs are equipped with trolleys that can move along the crane arm to transport the container from the ship to the quay area and vice versa. In unloading tasks, the spreader of a QC clutches a container on the ship, lifts it vertically to a safe height, moves it horizontally over the dock and places it either on a vehicle or on the ground (i.e. buffer area).

Typically, in container terminals two to six QCs work on a ship at a time, depending on the size of the containership, the number of containers to be unloaded and loaded, and the expected departure time of the containership. Conventional QCs can handle about 30-50 moves per hour [BAR 13]. However, the larger containerships force the CT authorities to expand the capability of the QCs. According to Chao and Lin [CHA 11] in the beginning of 2009, more than 18% of total capacity of worldwide containerships belonged to ships larger than 7500 TEUs. Since the first application of QCs in 1959 in Alameda CT – USA, the size of QCs has been doubled [BAR 13]. Nowadays, a Post-Panamax QC serves a ship with up to 65 meters in width (a row with 21–23 containers) and can lift a container 42 meters above its rail.

Selecting and using such expensive equipment is a multi-criteria decision-making process. Space restrictions and economic and historical factors are the key issues for port authorities when selecting the handling equipment for the CTs. One way to increase the throughput of the CTs is to replace the older equipment with a more efficient alternative. Dual-trolley QCs can work independently in two or more containers. In addition, modern spreaders make it possible to more two to four 20-feet-long containers simultaneously (twin-lift mode). An alternative way is to improve the scheduling methods for the QCs.

1.4.2. *Vehicles*

Loads are transferred to the yard for temporary storage. For the liquid bulk cargos, it is common to use pipelines, while for the dry and break-bulk cargo, yard trucks (YTs) are the most typical mode of transportation.

However, for the container, a wide variety of vehicles have been used since the beginning of containerization. Initially and for a period of time, only conventional YTs and rail-based handling equipment were used; mainly due to their comparatively low investment cost and large capacity. However, they need human drivers which lead to increasing operational costs [CAR 14a].

More recently, the choice has been automated guided vehicles (AGVs), which are completely automated; they are controlled by a central computer which decides on the dispatching and movement of each vehicle. However, AGVs are not able to lift the containers by themselves. Thus, they need a crane to receive and/or deliver the containers. AGVs have been widely implemented in modern automated container terminals, e.g. Euromax CT in Rotterdam, Netherlands and Pasir Panjang terminal in Singapore. AGVs usually follow a fixed path guided by markers, wires, lasers or computer vision; however, more intelligent and flexible AGVs have been introduced that travel freely in the transferring area, and avoid collisions and congestion. Today, AGVs can transport up to one FEU (single-load) or two TEUs (multi-load), in a trip.

Transport vehicles are classified as passive or active. Passive vehicles (e.g. yard trucks and AGVs) are not able to lift containers from the ground autonomously and thus, need to interact with other equipment, which requires a higher degree of coordination between the various equipment types. On the other hand, active vehicles (e.g. straddle carriers (SCs) and automated lifting vehicles (ALVs)) are not dependent on other equipment to lift a container. This means that they can lift and transport the containers between the ship and buffer area; although the size and availability of buffer areas is an important issue for the practical use of active vehicles.

Straddle carriers are able to stack containers on top of each other (usually up to 3 or 4 containers). Although this is a positive point for the SCs it causes a lower transportation speed of the SCs, because they are intra-mode transportation equipment. Moreover, if the CT operator decides to use SCs as a stacking crane, a special storage yard layout (in which only one container can be stored in a row) is needed, since SCs need clearance on both sides of containers in order to handle them. However, SCs are among the most adopted transportation/stacking equipment for small- and medium-sized container terminals. Note that typical SCs are manned. ALVs have been designed based on the concepts of SCs to lift/deliver the containers from/to the ground and to move them automatically and more quickly, similarly to an AGV. Obviously, ALVs have an independent work cycle from that of the QCs or the storage yard cranes and do not have to wait for a transport vehicle.

Initial simulation studies to compare AGVs and ALVs have shown that on average, the number of required AGVs in a CT is 50% more than that for the ALVs, in order to achieve the same performance [VIS 04, YAN 04]. Thus, ALVs are superior to AGVs in terms of productivity, as they reduce the waiting time in the buffer areas at the quay cranes. The AGVs fail to meet demands of tandem double-trolley QCs, where a pair of containers is ready to be unloaded in very short intervals; however, the ALVs are capable of serving such types of QCs [BAE 11]. However, Homayouni *et al.* [HOM 14] stated that by using more effective scheduling techniques (i.e. integrated scheduling), the required number of AGVs for a specific set of loading/unloading tasks can be decreased by half.

1.4.3. *Storage equipment*

The temporary destination of the loads in seaports is the storage yards. Stacking in a very large yard is the most common method of storage. A typical storage yard in CTs consists of multiple rectangular blocks, each of which consisting of several rows of containers stacked in tiers with up to six containers (see Figure 1.4). For a full description of the yard layout in CTs refer to [CAR 14b].

Yard cranes (YCs) are the most common yard handling system in CTs all around the world. YCs are non-automated rubber-tired gantry cranes, which have the flexibility to travel freely within the blocks. YCs can rotate their tires by 90° to move between the blocks as well, although this is a slow process (takes approximately 15 minutes [CAR 14b]). The second most used handling system in CTs is a straddle carrier, which is basic manual equipment to move the containers in the storage yard and stack them; however, it can only stack up to four containers. The containers self-lifting capability and the ability to move around the CT are the two most important characteristics of SCs. Thus, they are used in CTs both for transferring containers between the quayside and the storage yard, and for storing containers in the yard. However, a special layout for the storage yard is required to implement the SCs, since they can only move on the top of one row of the container. Automated yard cranes (AYCs) are also commonly used, however, since they are rail mounted gantry cranes, their movement is limited to the rails. AYCs can be operated without human intervention; although for safety reasons, when interaction with non-automated vehicles occurs, it is preferable to operate them manually. YCs and AYCs can move on the top of six rows of containers.

A simulation model was developed by Vis [VIS 06] to compare the performance of manned SCs and AYCs, in terms of average total travel (including both loaded and empty travels), hoisting and reshuffling times. They concluded that since there is no restriction of width (based on number of containers) for manned SCs versus AYCs, if the number of rows for each crane is between six and eight, then the AYCs outperform the SCs. However, for a block with nine rows or more SCs perform better than AYCs. In fact, SCs are the most suitable equipment for small-, with one berth segment [CHU 05], to medium-sized CTs [CAR 14b]. Nevertheless, for larger terminals, the land utilization and controlling issues may affect the performance of SCs; and they are outperformed by YCs and AYCs.

The main advantages of introducing new equipment in storage yards are the automation of equipment and its ability to use the land more efficiently. According to Stahlbock and Voß [STA 08], simple chassis-based lift trucks can store up to 250 TEUs/Hectare. The SCs can stack up to 750 TEUs/Hectare, while the higher number of stacked containers increases the land usage up to 1000 TEU/Hectare for YCs, and 1100 TEUs/Hectare for AYCs.

Once an exporting container of a specific ship is stored in a block, to decrease digging activities of cranes, the whole column (or columns in a row) of the location is reserved for containers of the same ship. The same happens when a portion of a block is dedicated to a shipment. Therefore, if the arrival of the whole shipment lasts for one or two weeks, the arriving containers are stored in the assigned portion of the storage block. In some other CTs, exporting containers of the same containership are often distributed among blocks to smooth the yard–block work balance, which leads to an additional vehicle traveling time. The reshuffling of the containers is another unproductive process in CTs; however, it is required when the desired container has been stacked below some other container(s). These are the main reasons for conventional yards to have storage land utilization indices much lower than the nominal capacity, regardless of the type of equipment used.

Increasing storage yard size is difficult, since, on the one hand, many container terminals have nowhere to expand and, on the other hand, land costs are sometimes prohibitive. In addition, reshuffling operations required in stacking storage yards are too time-consuming. Thus, to increase storage capacity researchers have recently been considering the principles of automated storage and retrieval systems to be implemented in CTs. For example, the split-platform automated storage/retrieval systems (SP-AS/RS) [CHE 03, HU 05], in which not only the land utilization is higher than the conventional storage yard, but also, storage and retrieval operations of various containers are not dependent on any other container in the storage area, which results in quicker access to containers and no reshuffling.

The storage system in the SP-AS/RS comprises several storage racks, each of which consists of two bays. Each of the bays has a certain number of rows accessible using the vertical platform (VP). Storage cells in each row are served using horizontal platforms (HPs). Load/unload (L/U) stations are places for the containers to be picked up/delivered to the vehicles. Expected travel time models for the SP-AS/RS have been developed by Vasili *et al.* [VAS 06], Hu *et al.* [HU 08] and Vasili *et al.* [VAS 08], and its physical and economic feasibility has been proved theoretically [HU 05]. More details of such a system and how to schedule storage and/or retrieval operations are provided in section 5.5.

1.5. Optimization of maritime operations

Optimization problems in maritime operations like any other major decision-making area are divided into three main levels, namely long-term or strategic, mid-term or tactical and short-term or operational. Decisions like cooperation between seaports, investment in new seaports or expansion of the current ones, seaport equipment type and degree of automation, ship fleet mix and size are among the strategic problems; while, decisions such as ship routing, storage yard layout and mid-term ship scheduling are usually categorized as tactical decisions. Real-time ship scheduling, speed optimization, berth allocation, crane scheduling and yard vehicle scheduling are among the day-to-day or operational decision problems. A schematic view of these decision levels is depicted in Figure 1.4. Note that each decision level imposes a set of constraints to the lower level of decision-making, while lower level decisions affect the level of accomplishment of the goals set by upper decision levels.

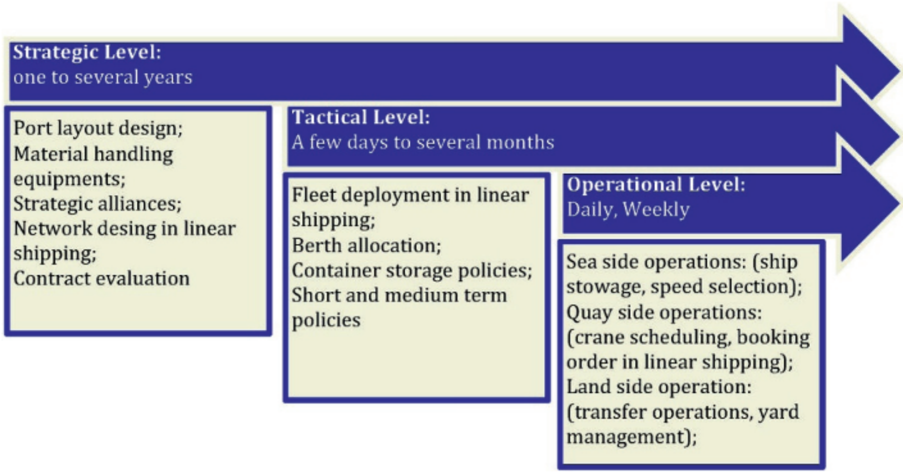

Figure 1.4. *Three levels of planning decision in seaports*

Owing to cumulative competition among geographically close seaports, the expected capacity of seaports has increased considerably, and forced the seaport authorities to improve the performance and productivity of the terminals. The efficiency of storage yards and handling equipment are key factors for more productive and efficient seaports. Massive containerships need to be unloaded/loaded in a shorter amount of time to reduce the inactive ships' time and this decreases maritime transportation costs. In most of the cases, both equipment and decision-making improvements are essential to decrease waiting times in seaports.

Although decisions made in strategic and tactical levels have a great impact on the performance of the seaports, the daily operations are the most challenging and time-consuming problems for the seaport authorities. Especially for container terminals, since, due to the degree of automation required, a very large number of complex problems needs to be dealt with. Figure 1.5 illustrates the main operational problems in maritime operations. The upper level decisions constrain lower level problem solutions dedicated by the available resources.

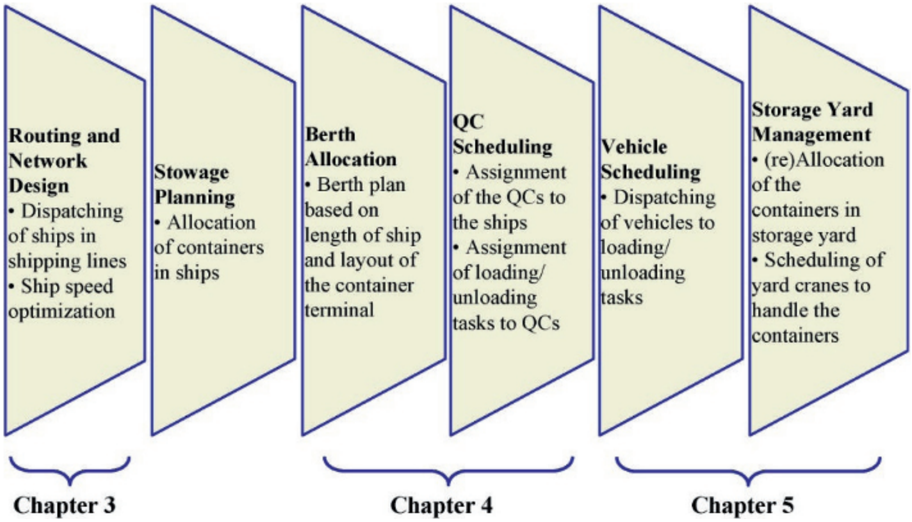

Figure 1.5. *Major operational problems in CTs*

Commonly, ships travel between multiple seaports around the world either based on a predetermined fixed or cyclic route (in liner shipping) or based on a route of demanded seaports (in tramp shipping). Designing the cyclic routes for liner shipping requires that one determines which ports the ships should visit, and in which order it should be done. Such decisions are, obviously, constrained by fleet size and ship type. Speed optimization of the ship along the route is another important issue. Traditionally, quick and shorter routes are the target of routing and network design problems [MEN 14]. However, energy-efficient routes and speed optimization problems have recently gained much more attention in the literature [PSA 13, PSA 14]. The most important output of the ship routing and network design problem is the estimated arrival time of a ship to the seaports. We focus on these problems further in Chapter 3.

Containers are stacked on top of each other in docks of containerships and are accessible only from the top of the stack. In stowage planning, each group of containers is stored in containerships based on the size and destination port. The most important objectives for stowage planning are to maintain containership stability and minimize the number of reshuffling operations required to reach demanded containers in the destination CTs.

The most important output of the stowage planning problem is a primary plan for unloading and loading the containers in the CT. A brief description of the problem is reviewed in Chapter 4.

Ships are allocated a berthing time and a position, prior to the arrival at a seaport. The berth allocation problem (BAP) determines these decisions based on the available berthing area, size of the ship, load type of the ship and its estimated arrival time. The main objective of the BAP is to minimize delays in service time for a group of ships in a mid-term planning horizon.

Once a ship moors at the berth segment, a number of QCs or (un)loaders are assigned to the ship. In container terminals, a set of QCs are assigned to each ship, included in the berth plan, with a known volume of containers to be loaded and unloaded – the quay crane assignment problem (QCAP). The QCs move along the berth area on a rail and cannot overtake each other. The objective of the QCAP is to assign cranes to ships such that all required loading and unloading operations are performed before the expected departure time of the ship (i.e. ship due date). A detailed schedule for the QCs to unload and load containers to a containership is the main outcome of the quay crane scheduling problem (QCSP), in which the makespan of the entire ship's operations is minimized. Precedence relations between the containers are the most important constraints for the QCSP. The BAP, QCAP and QCSP, and the integrated planning and scheduling approach to these problems are reviewed in Chapter 4.

The imported loads from a ship need to be transferred from the berth area to the storage yard, while the exported loads need to be transferred from the storage yard to the berth area. In the vehicle scheduling problem, a set of vehicles is assigned to a ship and dispatched to the loading and unloading tasks. The prime objective of the vehicle scheduling problem is to minimize the total traveling time of the vehicles and the makespan for all the loading and unloading operations.

In the storage yard, which is a massive buffer area between the maritime transportation and the customers or other modes of transportation, temporary storage blocks are allocated to the imported/exporting loads; this allocation problem is known as the storage space allocation problem (SSAP). The main objective is to maintain a balanced workload of the blocks and to minimize the storage/retrieval time of loads. On the other hand, scheduling of the cranes in the storage yard is important to minimize total delayed workloads, and the total travel time of the cranes moving between blocks. The SSAP, the vehicle scheduling problem and yard crane scheduling problem are reviewed in Chapter 5.

Although the afore-mentioned problems are mainly approached as described, there are dependencies or even overlapping among some of the decisions involved. For example, the best routing may lead to a ship arriving at a port that cannot handle it, for instance, due to the unavailability of berth segments or cranes. Recently, such problems have started to attract some attention; however, integrated decision-making problems are still predominant research areas for future studies. Chapter 5 also reviews them.

1.6. Conclusion

In this chapter, we reviewed some facts and figures that show the important role of maritime transportation in global, regional and national economies, and the increasing demand for the loading/unloading capacity in seaports and maritime transportation. The ever-increasing need for maritime transportation pushes for better equipment and for improvements in the effectiveness and efficiency of its utilization.

As we have seen, there are many different problems, each involving many aspects that can be optimized in order to increase maritime transportation efficiency; both regarding ship operations and seaport operations. This way, giving a competitive edge to this transportation mode, which is already responsible for over 85% of the goods transported worldwide.

Most of the problems in the operational level are NP-hard, and thus mathematical exact methods are not capable of providing solutions in a timely manner. Thus, the majority of the research reported addressing these problems proposes heuristic and metaheuristic approaches capable of finding good quality solutions within a reasonable amount of time. In Chapter 2, we review some of the most popular metaheuristics regarding the optimization of maritime operations.