Chapter 2
Container-Terminal Logistics

Within this chapter, the container terminal, as the major interface between the waterside and landside container-logistics sector, is introduced. At first, in Sect. 2.1, the container-logistics sector—including its development, its transport objects and its modes of transportation—is described. Afterwards, in Sect. 2.2, the container terminal along with its functions, related subsystems and equipment is presented. Thirdly, the assessment of container terminals by means of design and performance figures is explained in Sect. 2.3. In Sect. 2.4, an overview is given on planning problems that arise at seaport container terminals. Finally, some concluding remarks about this chapter are made.

2.1 Introduction to Container Logistics

According to the definitions of logistics and containers (Krieger 2005a,c), container logistics can be defined as the integrated planning, coordination, execution and control of all flows of standardised ISO (international organization for standardisation) 668 steel boxes and of the related information from the origin to the final destination. In comparison to conventional bulk transportation, the usage of containers has the advantages of less packaging, less damaging and being more productive (Hecht and Pawlik 2007, pp. 13–14). Nowadays, the oversea transport of finished consumer goods is almost always carried out in these standardised steel boxes—the so-called containers—on deep-sea container vessels. In addition, the fraction of liquids as well as piece and bulk goods shipped in specialised containers is also increasing (UNCTAD 2008, pp. 22–25). But the container logistics comprises more than just the oversea transport that is carried out by container vessels. Moreover, also stripping, stuffing, storing and handling containers as well as its hinterland transportation is included in the container logistics.

Examples of the intercontinental container-transport chain are given by Saanen (2004, pp. 1–2) as well as Hecht and Pawlik (2007, p. 89). In Fig. 2.1, a generalised

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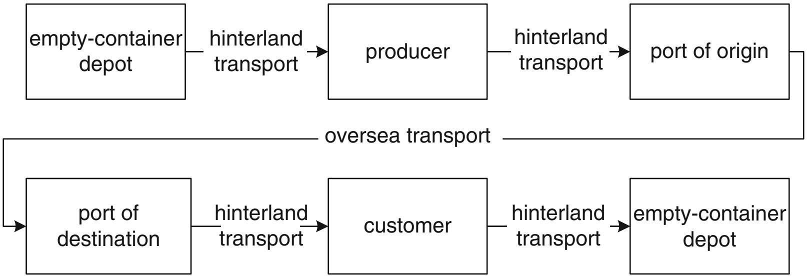


Fig. 2.1 Schematic container-transport chain (based on Hecht and Pawlik 2007, p. 89)

flow of containers within the framework of container logistics is illustrated. Usually, the flow of an unladen container starts at a special depot where only empty containers of certain carriers are stacked. From the empty depot, a container is transported by truck to the point where it is stuffed with cargo—which may be the producer of a certain good. Afterwards, the laden container is transported by hinterland modes of transportation to the next seaport container terminal from where it is shipped overseas to another container terminal. The hinterland transport is not necessarily executed by only one mode of transportation. Moreover, several modes can be involved, as the container may firstly be transported by truck to an inland container terminal from where it is transported by train to the seaport container terminal. Also the oversea transport may consist of several vessel journeys. Firstly, the container may be transported by a smaller vessel to a bigger port, from where it is shipped by means of a larger vessel to another port. From the port of destination, the container is then moved by hinterland modes of transportation to the customer, where it is stripped. Finally, the empty container is transported to the next empty depot of the corresponding carrier.

Altogether, container logistics play a major role in the supply chain of most producing companies. Subsequently, the history of the container logistics is described and its importance for the global economy is explained. Thereafter, different existing types and sizes of the standardised container are presented. Finally, all modes of transportation that may be involved in the container-transport chain are presented.

2.1.1 Development and Importance of Container Logistics

The triumphal procession of the civil container logistics began with a fleet of old oil tankers, which were bought in 1956 by the carrier Malcolm McLean. His shipping company—which is named Sea-Land—began to change the world of shipping and logistics immediately. On the 26th of April, 1956 McLean's modified tanker 'Ideal-X' left the port of Newark (New Jersey) in direction of Houston (Texas) with 56 containers on board. Subsequently, he established the first shipping services between the US-American East and West Coast. The great success induced the installation of international shipping services in the 1960s. Until the end of that decade, the first original container vessels had carrying capacities up to 700 containers. The success of the container logistics continued due to the standardisation of the container sizes by the ISO, which enables a simplified transshipment between international container-shipping lines and other modes of transportation (see Sect. 2.1.2). In the forthcoming years, special facilities with specialised equipment for container handling were built in the ports around the world—so-called container terminals (Hecht and Pawlik 2007, pp. 13–15).

During the last decades, the container volume handled world wide has continuously increased as a result of globalisation, economical growth and geographical distribution of activities. Before the economic crisis in the years 2008 and 2009, it has even been expected that this growth will continue for the next decades with annual rates of 5–8% (Saanen 2004, p. 8). However, first studies (Min et al. 2009) and current figures (Port of Hamburg 2011b) indicate that the path of growth will be continued in the future.

A lot of maritime transportation results from missing resources in the country of destination, while other cargo flows are induced by cheaper production costs in the country of origin than in the country of destination. Nowadays, the international trade is based on low transport costs, so that the difference in production costs between country of origin and destination do not need to be that big (Hecht and Pawlik 2007, pp. 16–17). During the last decades, the oversea transport costs of containers have been substantially decreased due to economies of scale which have been facilitated by continuously increasing vessel sizes (Scholtens et al. 1999, p. 7). While container vessels of the first generation (until 1970) had carrying capacities up to 1,000 containers, the vessels of the fourth generation (early 1990s) already had capacities of about 4,000 containers. Today, vessels with carrying capacities of more than 8,000 containers are increasingly common. However, the correct answer to the question of the world's largest container vessel has a rather short lifetime. In 2006, Maersk Line presented its 'Emma Maersk' with an officially announced capacity of 11,000 containers, but experts expect actually larger capacities of up to 14,300 containers (Hecht and Pawlik 2007, p. 47).

Along with the growth of vessel sizes, the requirements for the ports and the container terminals that handle these larger vessels are growing as well. Especially, the draught of the ports and the lifting height and outreach of the QCs have to be increased. But also the other terminal equipment has to be adjusted in order to handle and store more containers within similar periods of time. Therefore, huge investments are involved with the handling of the biggest container vessels, which cannot be afforded by every terminal. Thus, the hub and spoke concept has evolved (see Sect. 2.1.3), in which only some terminals—the hubs—handle the big vessels and other terminals—the spokes—only handle smaller vessels (Saanen 2004, pp. 8–16).

Altogether, container shipping and globalisation depend on each other. Without the success of the container logistics far less international trade could be expected, but at the same time the growth of the world trade with its division of labour induces the demand for container-shipping services and container-terminal capacities (Hecht and Pawlik 2007, p. 17).

2.1.2 Container Size and Type

In spite of its standardisation, several different sizes and types of containers have to be distinguished. However, all these different freight containers that are handled around the world are standardised according to the ISO 668 standard. The size of a container refers to its metrics in terms of length, width and height, which are usually expressed in feet and inches. The length of a freight container is either 20′, 40′ or 45′ and commonly used container heights are 0′, 8′, 8′6″ and 9′6″. A standardised ISO-container is always 8′ wide. A 9′6″ high container is usually called high-cube, whereas the 0′ high container is referred to platform containers, which only have foldable walls or even no walls (Nazari 2005, p. 5). Sizes and capacities of vessels and container terminals are generally measured in terms of TEU, which refers to the length of a 20′ container. Consequently, a 40′ container accounts for two TEUs. The tare weight of a 20′ container is around 2,250 kg and its maximum payload is 22,750 kg (Hecht and Pawlik 2007, p. 73).

Besides its size, a container can be classified according to several other characteristics. On the basis of its cargo, a container can be classified into the main types dry container, tank container, open container and reefer (Nazari 2005, p. 5). A dry container is a closed standard container with two doors which is used for carrying solid cargo without any special requirements. A tank container is used for carrying liquids or gases. It consists of a tank surrounded by a metal frame that enables stacking like for dry containers. An open container does not have a roof and some walls may be missing too. It is designed for carrying OOG (out of gauge) cargo which is slightly higher or wider than will fit standard dry containers. Some commonly used open containers are open top (i.e., having no roof), open side (i.e., having no side walls), flat racks (i.e., having only foldable end walls) and platforms (i.e., having no walls). A reefer is a dry container which is designed for carrying cargo that needs to be refrigerated. Two types of reefer can be distinguished: conair-container and integral reefer. While integral reefers have an incorporated electric cooling unit, conair-containers need a special clip-on cooling unit in case the container is used for cargo that requires refrigeration (Hecht and Pawlik 2007, pp. 76–79). Nowadays, the oversea transport of finished consumer goods is almost always carried out in dry containers. The other types only make up for a fraction of about 15% of the turnover of a container terminal (Petering et al. 2009).

In addition, a container may be classified according to its load or IMO status (international maritime organization). The load status of a container, which is either full or empty, is required for the stacking operations, as container weight matters and empty containers are often stored in special empty-container blocks. The IMO status of a container indicates which kind of special handling and storage is required, in case dangerous goods are loaded (Nazari 2005, p. 5). Subsequently, the term container is mostly used as synonym for the standard dry container with lengths of 20′ and 40′.

2.1.3 Types of Container-Transport Modes

The container transport is realised by several different modes of transportation. The waterside transport is carried out by vessels (see Fig. 2.2) and the landside transport is executed by XTs (external truck) and trains. Depending on its routes, carrying capacities and other characteristics, the following types of transport modes can be distinguished (Nazari 2005, p. 6):

Deep-sea vessels travel the long oversea distances between different continents and larger areas. Usually, deep-sea vessels have huge carrying capacities of several 1,000 TEUs and they are mainly used for interlinking Europe, North America, South America, the Far East and the Middle East. Lengthwise, the carrying capacity of deep-sea vessels is subdivided into several holds which consist of several bays with the length of 20′ or 40′ containers. Containers may be stacked on deck or below deck. For a detailed description of deep-sea vessels it is referred to Hecht and Pawlik (2007, pp. 25–38). Today, a deep-sea vessel usually calls at several ports on a cyclic route and in each port containers are discharged and loaded. The containers that are loaded onto the vessel are destined for subsequent ports on its route (Meersmans and Dekker 2001).

Short-sea vessels travel shorter distances across the small seas, mostly between countries of the same continent. Usually, the carrying capacities of short-sea vessels are a lot less than for deep-sea vessels, often only several 100 TEUs.

Feeder vessels travel comparable distances and have similar-sized carrying capacities like short-sea vessels. But in contrast to short-sea vessels, they carry containers that come mainly from or are destined for deep-sea vessels.

Barges are small vessels that do not usually travel overseas, instead, they mainly serve the hinterland of a seaport via rivers and channels. They only have carrying capacities of several dozen TEUs.

XTs also serve the hinterland of seaport container terminals. They transport containers overland by usage of roads and usually have carrying capacities of only 2 TEUs. However, depending on the legal regulations, longer XTs with bigger capacities are possible.

Trains transport containers overland to hinterland destinations of seaport container terminals. Its carrying capacity depends on the number of deployed rail cars and may be up to 90 TEUs (Boysen and Fliedner 2010).

Altogether, a seaport is connected to other oversea ports by deep-sea, short-sea and feeder vessels and it is connected to the hinterland by XTs, trains and barges. Depending on the flow direction of a container, it is either imported, exported or transshipped at a seaport container terminal. The corresponding container flows are summarised in Table 2.1. An import container arrives by vessel and leaves the terminal by XT, train or barge, while an export container is delivered by XT, train or barge and departs via vessel. Transshipment containers both arrive and depart by vessel.

Fig. 2.2 Example illustration of deep-sea vessel (*left*) and feeder/short-sea vessel (*right*)

Table 2.1 Classification of container flows at seaport container terminals

		Leave terminal via	
		Deep-sea Short-sea Feeder	Rail Road Barge
Arrive at terminal via	Deep-sea Short-sea Feeder	Transshipment	Import
	Rail Road Barge	Export	Land-land

The feeder and deep-sea vessels are part of the concept of hub and spoke container terminals which has emerged due to orientation towards economies of scale. While the transshipment from deep-sea to feeder vessels and vice versa takes usually place at large hub container terminals, the spoke terminals are generally smaller terminals which only serve smaller feeder and short-sea vessels (Nazari 2005, pp. 14–15). Most arriving containers at typical hub terminals are transshipped, whereas containers at spoke terminals are mostly imported or exported. The largest port in the world—Singapore—is a typical hub, as 80% of the handled containers are transshipment. A terminal with such a container flow is also called transshipment terminal. In contrast, the largest European port (see Table 1.1)—Rotterdam (Netherlands)—is not a transshipment port, as most containers (70–80%) are either imported or exported. Therefore, a container terminal with such a container flow is called import-export terminal (Saanen 2004, p. 11).

2.2 Introduction to Container-Terminal Systems

In general, a seaport container terminal is an open system of material flow with two external interfaces. At the waterside interface—which is the quay wall—vessels and barges are loaded and discharged, while at the landside interface trains and XTs are served. The storage area for containers facilitates as decoupling point of waterside and landside operations (Steenken et al. 2004). Furthermore, a container terminal can be considered as a rather sophisticated system of which the main attributes are its functions, its main operations and its resources (Saanen 2004, pp. 27–33). In the following subsections, these attributes are explained and discussed in detail. Firstly, the functions of the whole terminal system are explained. Thereafter, the subsystems of a container terminal and the relevant operations are described. Finally, different types of terminal equipment are presented.

2.2.1 Container-Terminal Functions

In Fig. 2.1, it is shown that the seaport container terminal plays a major role within the container logistics, as it is the interface between the oversea and hinterland transport. The primary functions of a container terminal are shown in Fig. 2.3, which illustrates the role of the container terminal in more detail. In particular, these are the transshipment from one mode of transportation to another as well as the temporary storage of containers. In addition, some secondary functions are fulfilled by the container terminal which may be summarised as added services (Saanen 2004, pp. 27–29; Nazari 2005, pp. 17–19).

The transshipment function—which should not be confused with the transshipment container (see Sect. 2.1.3)—refers to discharging and loading vessels, barges, XTs and trains. The added value of theses processes is provided by the speed at which vessels are handled and the decoupling of oversea transport and hinterland transport. However, direct transshipment from one mode of transportation to another is nearly impossible. Therefore, the storage function of a container terminal is of particular importance for the performance of the container terminal (Saanen 2004, p. 28). Some reasons for the essential importance of the storage function are provided by Zijderveld (1995, pp. 2–3):

- The terminal process would become too complicated in case of direct transshipment, since all individual XTs would have to be controlled in such a way that they arrive in the right sequence, at the right time and at the right place in order to process the relevant transshipment operation without any delays.
- For terminals with more than two different modes of transportation, direct transshipment would require a sophisticated terminal design. All handled modes of transportation have to be located very close to each other, which would cause serious problems for terminals with deep-sea vessels, barges, trucks and trains.
- Both individual means of transportation between which containers are transshipped have to be simultaneously present if containers are transshipped directly. Especially for transshipment between two vessels as well as between trains and vessels it is virtually impossible, as vessels and trains may be very long and sequence relations for loading and unloading of vessels and trains would have to be simultaneously respected.

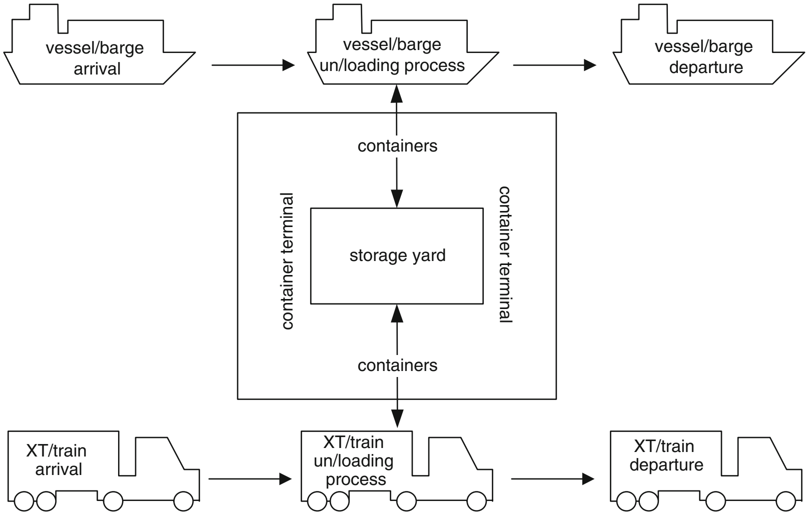


Fig. 2.3 Schematic processes of container terminals (based on Saanen 2004, p. 28)

- The receivers of a container do not always need their cargo very fast. Thus, they are not always interested in direct transshipment, in contrast, they may be interested in inexpensive storage possibilities. In addition, containers have to be stored on the terminal due to customs demands and financial requirements. Some containers stay even longer than 6 months on the terminal (Saanen 2004, p. 29).

Usually, container terminals provide sufficient area for the storage functionality. This storage area is often subdivided into smaller areas for the storage of special container types like reefer, empty container and IMO container. The total size of a storage yard is determined by the terminal-specific throughput and the average container-dwell time. Most container terminals are interested in a high throughput and short container-dwell times, since their original business model is usually based on the transshipment of containers and not their storage. Therefore, the storage function of container terminals cannot be compared with that of a typical warehouse. Moreover, it is like a buffer in order to facilitate the transshipment function. Reasonable container-dwell times in the sense of the buffer function are normally 3–8 days (Nazari 2005, p. 18). Altogether, the storage yard at seaport container terminals provides relatively inexpensive, secure and easily accessible buffer storage locations, from which JIT (just in time) deliveries of containers can take place (Saanen 2004, p. 28).

Container terminals may offer several added services, which can be qualified as inessential secondary terminal functions. Some of these functions are stripping and stuffing of containers in a CFS (container-freight station), container repair and washing as well as equipment maintenance. Furthermore, some terminals may offer a depot function for empty containers and shipping-line-owned road chassis (Saanen 2004, p. 29; Nazari 2005, p. 19).

2.2.2 Container-Terminal Subsystems and Related Operations

The container terminal is a rather complicated system with several interrelated types of operations, numerous controllable objects (equipment) and thousands of plannable items (jobs, containers). Thus, the terminal is often subdivided into several subsystems according to the related operations and the equipment involved (Steenken et al. 2004). Here, the whole terminal system is viewed to consist of the ship-to-shore subsystem, the waterside horizontal-transport subsystem, the storage subsystem and the hinterland-connection subsystem.

Despite this division into several subsystems, the handling capacity and the performance of the whole terminal system is determined by all of the subsystems, which means that the subsystem with the smallest handling capacity determines—as the bottleneck—the handling capacity of the container terminal as a whole (Nazari 2005, pp. 9–10). Since the different subsystems are linked with one another, each subsystem should be designed and managed in such a way that the connected subsystem(s) may be operated most efficiently. Subsequently, the general layout of a container terminal along with the positioning of the subsystems is introduced. Thereafter, each of the subsystems is described in detail.

2.2.2.1 Container-Terminal Layout

Hundreds of container terminals with different layouts, different container-handling concepts and different types of equipment exist around the world. Nevertheless, most terminals have a comparable arrangement of their subsystems and facilities, which is schematically shown in Fig. 2.4.

Of course, the ship-to-shore subsystem is located at the waterside edge of the terminal where quay cranes are used to load and discharge vessels and barges. In general, the ship-to-shore subsystem is followed by the horizontal-transport subsystem, which is responsible for the transport of full and empty containers between the quay cranes and the storage subsystem. Usually, this horizontal transport is executed by different types of transport vehicles.

The storage subsystem is the place on the terminal where containers are temporarily stored. Besides the regular storage area, most container terminals exhibit a special empty depot where empty containers are stored according to the needs of the shipping lines (Steenken et al. 2004). In addition, most facilities for the added services that are offered by container terminals may be assigned to the storage subsystem. Here, a CFS and facilities for maintenance and repair of containers are linked with the storage subsystem. Due to its decoupling function between waterside and landside terminal operations, the storage subsystem is located in the centre of the terminal. According to its main function, the regular storage area takes up most of the space of the storage subsystem.

On the landside, the storage subsystem is followed by the hinterland-connection subsystem, which fulfils the function of an interface between the terminal and

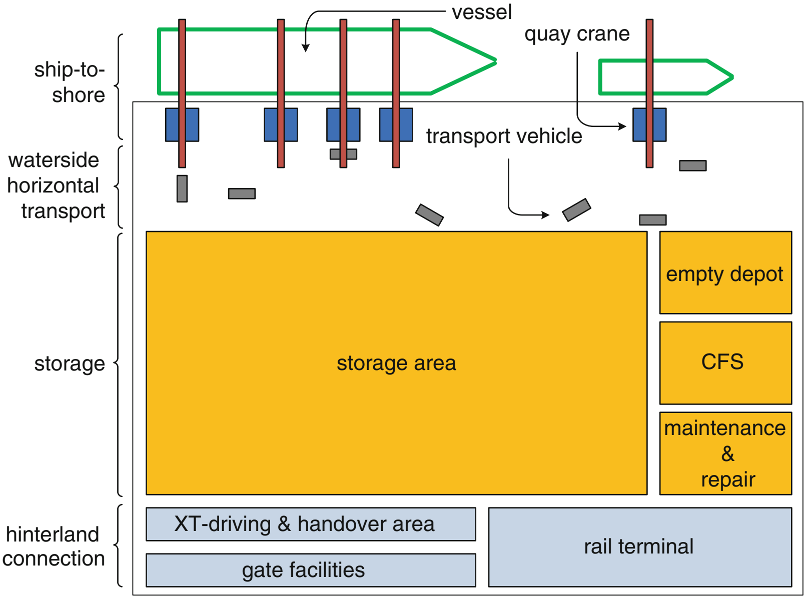


Fig. 2.4 Schematic terminal layout

its hinterland. As both XTs and trains act as landside connecting modes of transportation of seaport container terminals, the hinterland-connection subsystem may comprise facilities for both modes. Trains are loaded and discharged at the rail station of the terminal by special equipment—usually gantry cranes (Meersmans 2002, pp. 8–10). XTs enter the terminal at the gate facilities, where they are checked and administrative tasks are fulfilled. Next, the XTs drive on dedicated streets or driving areas to a handover area where the relevant container is loaded onto or discharged from the XT by special terminal equipment.

2.2.2.2 Ship-to-Shore Subsystem

The ship-to-shore subsystem is designated to the loading and discharging operations of vessels. As it is the direct interface to one of the terminals most important group of stakeholders—the shipping lines—the ship-to-shore subsystem is often regarded as the key subsystem of seaport container terminals (Nazari 2005, pp. 10–11). Several operational planning problems of container terminals are related to the ship-to-shore system. These problems are the stowage planning for deep-sea vessels as well as berth and QC allocation for arriving vessels. An introduction to these planning problems along with a brief overview on the relevant literature is provided in Sect. 2.4.

Before the loading and discharging process of containers begins, the relevant vessel has to moor at the quay of the terminal. As illustrated in Fig. 2.4, several berthing places are available at most container terminals (Meersmans and Dekker 2001; Vis and de Koster 2003). Usually, a vessel is assigned to a berthing place prior to its arrival. In case the arriving vessel is part of a liner service, normally the same berthing place is assigned to each arriving vessel of that service. Nowadays, most arrivals of deep-sea vessels follow a periodically repeated vessel-call pattern, which usually consists of weekly or 2-weekly arrivals for each calling liner service. Besides berthing places, also specific QCs have to be assigned to the loading and discharging processes of calling vessels prior to their actual arrival. While feeder vessels are usually served by one or two QCs, deep-sea vessels—depending on their size—may be served by four to six QCs (Steenken et al. 2004).

After a vessel has moored at the assigned berthing place, the discharging process begins. The containers which have to be discharged and loaded at the terminal are in practice usually only known shortly before the arrival of the vessel. While an unloading plan contains information on the containers that have to be unloaded and in which bay of the vessel they are located, the loading or stowage plan indicates which containers have to be loaded onto the vessel, in which sequence and in which bay they should be stacked. The number of all containers that have to be discharged from and loaded onto an individual vessel at the terminal is usually called moves per call and determines the workload for the QCs. Firstly, the containers that are listed in the unloading plan are successively discharged by the assigned QCs. Usually, the crane driver is free to determine the sequence in which containers are discharged within a specific hold. Since the discharging time for an individual container depends on its position on the vessel and the skills of the crane driver, a large variance in the discharging times is observed. After a QC has finished its discharging operations, it starts loading the containers that have to be stowed in holds to which the relevant QC is assigned. As the workload may be imbalanced between different cranes and due to the variance in the discharging times, it may occur that some cranes already start the loading operations while other QCs are still discharging. As container size and weight as well as the sequence in which the ports are visited by the relevant vessel have to be respected during the loading process, there is hardly any flexibility in the loading operations (Shields 1984); the crane drivers have to follow the stowage plan for the vessel accurately. After all QCs have finished the loading operations for a specific vessel, it unmoors and continues its tour to the next port (Vis and de Koster 2003).

The major objective of the ship-to-shore subsystem is the minimisation of the turn-around times (i.e., the berthing times) of vessels (Steenken et al. 2004). Hence, along with the steadily growing vessel sizes, the requirements for the ship-to-shore subsystem have increased as well. The terminals are faced with an increasing pressure on the ship-to-shore subsystem in terms of size and productivity of the QCs. Ever-increasing moves per call have to be handled during nearly unchanged berthing times—a typical deep-sea vessel should be turned in approximately 24 h (Rijsenbrij and Wieschemann 2011). As a consequence, high investments into new crane equipment are made (see Sect. 2.2.3) and much effort is spent on the development of elaborated planning methods (see Sect. 2.4).

2.2.2.3 Waterside Horizontal-Transport Subsystem

The waterside horizontal-transport subsystem acts as the interface between the ship-to-shore subsystem and the storage subsystem. Containers that are discharged by QCs are transported by horizontal-transport vehicles from the QC to the storage yard, and before containers can be loaded onto a vessel, they have to be transferred from the storage yard to the QCs. The general objectives of this subsystem are efficient, smooth and fast transfer of containers between the QCs and the storage yard (Nazari 2005, pp. 11–12). In order to achieve these aims, the right decisions on type and number of applied transport machines as well as on scheduling and routing of the machines have to be made (Vis and de Koster 2003).

The container transfer between QCs and storage yard may be executed by different types of transport vehicles, which differ in carrying capacity, flexibility, velocity, degree of automation and other characteristics. However, the horizontal-transport processes are most of all affected by the container-lifting capabilities of the transport vehicles (see Sect. 2.2.3.2). In case the vehicles have no lifting capability, they have to be loaded and discharged at the QCs and storage yard, which means that some additional stacking equipment is needed in the yard area. Hence, a smooth and timely coordinated transfer between QCs and stacking equipment is of major importance for the productivity of the whole terminal system, as otherwise some of the involved equipment has to wait for each other and valuable equipment resources are wasted. However, if the transfer vehicles are equipped with a container-lifting device, they are able to load and discharge containers themselves. Consequently, horizontal-transport vehicles with lifting capability do not depend on the lifting capabilities of the QCs and stacking equipment. Thus, the interdependency of the ship-to-shore, horizontal-transport and storage subsystem is reduced—these subsystems are slightly decoupled from each other (Meersmans and Dekker 2001; Steenken et al. 2004; Saanen 2007).

Different transport cycles and QC-allocation schemes have to be distinguished for the horizontal-transport vehicles. The vehicles can either be exclusively assigned to one QC (dedicated allocation scheme) or several different QCs (pooled allocation scheme). In addition, the vehicles can either be operated in the single-cycle or dual-cycle mode. Within the single-cycle mode, the vehicle either transports containers only from the storage yard to the QCs or vice versa, while in the dual-cycle mode the vehicles transfer containers in both directions. In general, the single-cycle mode is connected with the dedicated allocation scheme, whereas the dual-cycle mode requires the pooled allocation scheme (Steenken et al. 2004).

Furthermore, there are differences in the transfer direction of containers. For container transfers from the QCs to the storage yard, no sequences have to be respected, which means that the containers do not need to arrive at the storage yard according to a certain schedule, whereas for the vessel-loading process the containers have to arrive at the QCs according to the scheduled stowage plan. Therefore, the transfer to the QCs has to be planned in such a way that different transportation times and the stowage plans are respected. Otherwise, the horizontal container transport would be connected with congestions at the QCs and stacking equipment as well as unproductive idle times for QCs, stacking equipment and transport vehicles (Meersmans and Dekker 2001; Steenken et al. 2004).

2.2.2.4 Storage Subsystem

The storage subsystem is probably the most important subsystem as it is the actual decoupling point between the waterside and landside container-transportation chain (Nazari 2005, p. 12). Since steadily increasing container volumes have to be stored in the storage yards and at the same time space is an increasingly scarce resource, the importance of the storage subsystem has continuously grown over the last years along with the increasing traffic volume (Steenken et al. 2004; Rijsenbrij and Wieschemann 2011). In this subsection, only a short introduction into the field of container storage is given, since it is the major research object of this work and detailed descriptions on the underlying operations and the applied equipment are provided in Chap. 3.

Superficially, two ways of storing containers at seaport container terminals can be distinguished. Firstly, containers may be stored on chassis, which enables direct access to each individual container. Secondly, containers may be stacked on the ground and piled up. Hence, not every single container is directly accessible. In order to get access to containers that are stored below others, the upper ones have to be shuffled, which means that they have to be repositioned to other storage locations (Meersmans and Dekker 2001). Nowadays, due to limited storage space, storing containers on the ground is most common, while storage on chassis is only partly used in North America (Vis and de Koster 2003; Kalmar 2011a).

Storage yards in which containers are stacked on the ground are usually separated into several blocks that consist of several bays, rows and tiers. The maximum stacking height (i.e., the maximum number of tiers) depends on the used stacking equipment. Most container terminals form separated blocks according to the attributes of the containers. There are different yard blocks for containers that are planned for vessel loading and that are planned for hinterland departure. In addition, there may be special storage areas for empty, IMO and damaged containers as well as for reefer. The storage yard of large European container terminals is on average filled with about 15,000–20,000 containers.

When an XT or an internal transport vehicle without lifting capabilities arrives laden at the interfaces of the storage yard, the container is discharged by some kind of stacking equipment. The container is then transferred by the stacking equipment to the dedicated stacking position in the yard block. If an XT or internal transport vehicle arrives empty at a yard block, the stacking equipment picks up the demanded container in the block and positions it on the corresponding vehicle. However, in case the internal vehicles are equipped with lifting devices, no additional stacking equipment may be required. Depending on the storage-yard system, the vehicles may drive into the block and pick up or position containers in the block themselves (Meersmans and Dekker 2001). In addition, there may be internal transfers between the different storage areas that are depicted in Fig. 2.4. While full containers in the main storage area may be transported to the CFS for stripping, empty containers may firstly be transported to the CFS for stuffing and afterwards moved to the main storage area for further transshipment. Furthermore, due to imbalances in the distribution of empty containers, they may be needed for transfer by vessel, truck or train and thus they have to be moved to the respective yard or transition area. Other reasons for internal transports are named by Steenken et al. (2004).

As most of the terminal operations either originate or terminate at the yard block, efficient stacking is of crucial importance for the effective execution of the remaining terminal operations. The efficiency of the stacking operations is determined by strategical decisions on the stacking equipment and the yard-block layout as well as by operational decisions about container stacking and about the scheduling and routing of the stacking equipment (Meersmans and Dekker 2001; Vis and de Koster 2003). These decisions usually have to be made with respect to the available space, the planned container throughput, the expected container-dwell time, the planned yard utilisation as well as external regulations concerning customs control, environmental protection and occupational safety (Nazari 2005, p. 12).

2.2.2.5 Hinterland-Connection Subsystem

The hinterland connections are of great importance for the competitiveness of container terminals. Without a fast, highly available, reliable and regular connection between the terminal and its hinterland, the flow of import and export containers would be impaired, which would harm the terminal performance as a whole. According to the modes of transportation, that are named in Sect. 2.1.3, connections by street, rail and waterways have to be distinguished (Nazari 2005, pp. 12–13).

XTs arrive by street at the gate of the terminal either laden or empty. While the containers of laden XTs are checked at the gate along with the corresponding data, the retrieval of certain containers is declared by empty arriving XTs at the gate. Afterwards, the XTs drive to dedicated handover areas, where they are either discharged or loaded by internal stacking equipment. In container-storage yards that are operated by yard cranes, the handover areas are usually located directly adjacent to the yard blocks and the XTs are served by the cranes. Whereas the XTs may also be served by internal transport vehicles with lifting capabilities if this technology is applied in the storage yard. Depending on the modal split, large European container terminals handle several thousand XTs per day (Steenken et al. 2004).

Most European seaport container terminals are connected with the public railway network. As a consequence, these terminals have their own rail stations where containers are loaded and discharged for ongoing transportation to hinterland and oversea destinations, respectively. Terminal machines are needed for loading and discharging of rail containers as well as for transfer of these containers between rail station and container-storage yard. The rail station is connected with the storage yard by internal transport vehicles with lifting capabilities or by internal trucks and trailers. If trucks and trailers are used, the containers are directly buffered on trailers alongside the rails, whereas two possibilities exist in case internal transport vehicles with lifting capabilities are deployed. Firstly, the containers may be buffered in container stacks alongside the rail. Secondly, the containers may be directly loaded on and discharged from the train by the internal transport vehicle which is able to drive over the waggons to pick up and drop off the containers. In case containers are buffered alongside the rails, the loading and discharging operations of freight trains are executed by special gantry cranes, which is the most common handling equipment for rail terminals (Steenken et al. 2004).

Freight trains may be up to 700 m long and carry up to 90 TEUs (Boysen and Fliedner 2010). The requirements of the loading and discharging operations of these trains are quite similar to those of deep-sea vessels. For each container that has to be loaded onto a certain train, the specific position on the waggons of the train are given by the relevant loading plan. This position is determined by type, weight and destination of that container as well as by the maximum load of the waggon and its position in the sequence of the train. A loading plan is either produced by the train operator or the container terminal. While the former one is interested in the minimisation of shunting moves during further train transport, the terminal is primarily interested in the minimisation of required shuffle moves in the storage yard (Steenken et al. 2004).

2.2.3 Container-Terminal Equipment

After having described the processes of the different subsystems of seaport container terminals in the previous subsection, this subsection is devoted to the equipment that is involved in the relevant operations. Equipment issues are of great importance for container terminals, as decisions on type and number of terminal equipment greatly influence the terminal design and operations (Saanen 2004, p. 31). Here, different types of equipment along with the corresponding attributes, facts, figures and operational restrictions are presented in order to facilitate a substantiated understanding and evaluation of explanations and assumptions that are made within the later chapters. According to the division into subsystems, the equipment overview is subdivided into quay cranes, horizontal-transport machines and storage equipment.

2.2.3.1 Quay Cranes

QCs—which are sometimes also called ship-to-shore cranes or simply gantry cranes—are used for loading and discharging vessels at container terminals (Nazari 2005, p. 6). At international seaport container terminals numerous types of QCs are in operation, which differ in size, handling capacity, logistical concept and other attributes.

First of all, there are two main types of QCs, which are mobile harbour cranes and rail-mounted gantry cranes. The former one is rubber-tyred and therefore it is more

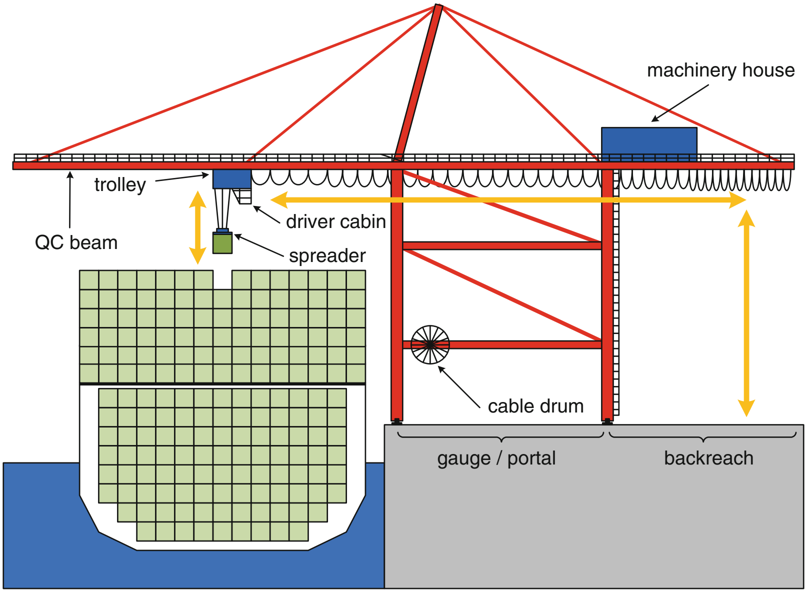


Fig. 2.5 Schematic illustration of QC

flexible than its rail-mounted opponent, which has only limited moving abilities. However, nowadays, modern container terminals mostly deploy rail-mounted gantry QCs, as they offer higher productivities, which means that they handle containers at higher speeds, and they are better suited to cope with the steadily increasing vessel sizes. While in practice mobile harbour cranes are used to handle vessels up to 13 containers wide on deck, the latest rail-mounted gantry QCs can handle vessels up to 26 containers wide on deck (Saanen 2004, pp. 31–32; ZPMC 2009). For that reasons, only the rail-mounted gantry crane is considered in this work and subsequently the term QC is used as synonym for this type of crane.

The three-dimensional movements which are required for loading and discharging of vessels are performed by three moving components of a QC: portal, trolley and spreader. In order to be able to load and discharge containers to/from different bays or even vessels, the portal (i.e., the whole QC) can move on rails alongside the quay wall. Due to being fixed to rails, QCs cannot pass each other, which means that their positions in the quay wall order cannot be changed. A schematic illustration of a commonly used QC is provided in Fig. 2.5, where typical QC movements for loading and unloading of containers are indicated by yellow arrows. It is shown that QCs are equipped with trolleys that are connected with spreaders by means of cable winches. The trolley can drive along the quay-crane beam and it is responsible for the transfer of containers between ship and shore. Onshore containers may be picked up or dropped off by the QC in two different zones, which considerably differ in the required driving distances for the trolley. Depending on the equipment type used for the horizontal transport, the organisational worklflows and the positioning of the hatch covers of the vessels, containers may either be handled in the backreach or in the portal/gauge of the QC. The spreader is a special device to pick up containers (Vis and de Koster 2003). It is equipped with pins that exactly fit into the openings which are located at each corner of a container. By turning the pins, the container is closely linked with the spreader, which enables loading and discharging of the container onto/from vessels. By means of the cable winches the spreader can be lowered or hoisted to the level a container has to be dropped off or picked up (Hecht and Pawlik 2007, p. 102). Common QCs are completely man-driven, which means that all movements of portal, trolley and spreader are controlled by the crane driver who is located in a cabin that is connected with the trolley (Steenken et al. 2004). A clear description of the crane-driver job is provided, for example, by Hecht and Pawlik (2007, p. 106).

The competitiveness of large container terminals greatly depends on the technical specifications of the deployed QCs. The trend towards larger vessels requires larger and faster QCs. In order to load and discharge containers properly, in particular onto/from the largest vessels, the clearance and the outreach of the QCs have to be increased. As a consequence, the handling times for container-loading and discharging operations increase as well due to longer driving distances for trolley and spreader (Saanen 2004, p. 32). Therefore, container terminals and crane manufacturers are continuously striving for increases in the QC productivities, in terms of the number of loaded and discharged containers per QC-working hour (see Sect. 2.3). The productivity may be increased by shortening the required time for QC moves and/or by handling more containers per QC move. While the former one is facilitated by shortening the horizontal driving distances for the trolleys as well as by increasing the maximum velocities and accelerations of trolleys and spreaders, the development of new spreader technologies allows for handling more than one container per QC move. A detailed table on the ranges of velocities and accelerations of different QC types is provided by Stahlbock and Voß (2008) along with other technical QC figures.

While conventional telescopic spreaders can either handle a single 20′, a single 40′ or even two 20′ containers simultaneously, the latest spreader technology—which is called tandem or twin 40′—allows for handling up to two 40′ or even four 20′ containers simultaneously. This is facilitated by attaching two standard telescopic spreaders with independent hoisting systems to each other. However, the tandem spreader technology puts increasing pressure on the crane-driver abilities, the stowage planning and the horizontal-transport processes, as all containers have to be simultaneously and accurately picked up and dropped off on land and on vessel (Johansen 2006; Kalmar 2011a).

The double-trolley QC is a rather new development that is designed to reduce the horizontal driving distances for the trolleys (Steenken et al. 2004). While single-trolley QCs require the only trolley to drive the whole horizontal distance between ship and shore, for double-trolley QCs this driving distance is shared between the man-driven main trolley and the preferably automated portal trolley, which allows for more container movements in the same period of time. The main trolley moves containers between the vessel and the lashing platform, that is located in the lower seaside part of the portal. The container movements between the lashing platform and the horizontal-transport system on shore is then performed by the portal trolley, which can drive along a portal beam between the lashing platform and the backreach of the QC (Steenken et al. 2004; Kalmar 2011a). The lashing platform is required as a container buffer and—due to occupational safety—as decoupling point between the manually controlled main trolley and the automated portal trolley. Double-trolley cranes are in operation, for example, at the CTA in Hamburg (Germany) (Stahlbock and Voß 2008).

Altogether, the handling speed of QCs and their maximum performance depends on the crane type. Today, modern QCs can technically perform around 50 loading and discharging moves per hour, while in operation usually only 22–30 moves per hour are realised (Steenken et al. 2004; Saanen 2004, p. 46). Considering the latest spreader technologies, even 80–100 40′ containers may technically be handled per QC working hour (Stahlbock and Voß 2008). Depending on size and other technological specifications, the prices for the latest QCs are in the range from 6,000,000 € to 9,000,000 € (ZPMC 2009).

2.2.3.2 Horizontal-Transport Machines

The vehicles that are used for the horizontal transport between the quay cranes and the storage area vary considerably at international container terminals. However, four vehicle types may be identified that are used with different characteristics at almost all terminals: SCs (straddle carriers), AGVs (automated-guided vehicles), TTUs (truck-trailer units) and MTSs (multi-trailer systems) (Vis and de Koster 2003; Steenken et al. 2004). These four vehicle types are schematically illustrated in Fig. 2.6.

Horizontal-transport vehicles can be classified into two different classes: passive and active vehicles. While passive vehicles are not able to lift containers by themselves, active vehicles are equipped with a container-lifting device that enables to load and to discharge containers by themselves. Passive vehicles require the assistance of other terminal equipment with container-lifting capabilities for loading and discharging containers. At the waterside interfaces of the horizontal-transport system, these loading and unloading operations of passive vehicles are carried out by QCs, while different possibilities exist at the landside (see Sect. 2.2.3.3). In contrast to AGVs, TTUs and MTSs which belong to the class of passive vehicles, SCs are classified as active vehicles (Steenken et al. 2004).

MTSs consist of a tractor that pulls several trailers, each with a carrying capacity of two TEUs. In Fig. 2.6d, such an MTS with three trailers is depicted, but even longer MTSs with four or five trailers are possible. On its journey across the container terminal, several destinations are visited by an MTS where some containers may be discharged, some new containers may be loaded and some containers stay on the MTS for further transfer to upcoming destinations (Kalmar 2011a).

TTUs are technically quite similar to MTSs, as they also consist of tractors and trailers. But here only a single trailer with a carrying capacity of two TEUs is pulled

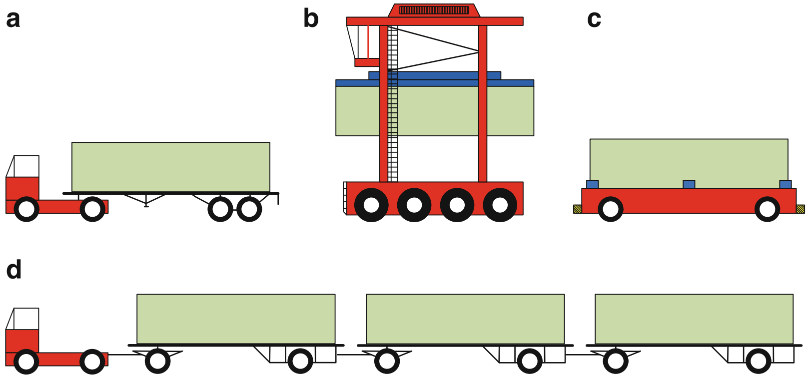


Fig. 2.6 Schematic illustration of horizontal-transport vehicles. (**a**) Truck-trailer unit (TTU). (**b**) Straddle carrier (SC). (**c**) Automated-guided vehicle (AGV). (**d**) Multi-trailer system (MTS)

by each truck (see Fig. 2.6a). Thus, on the one hand, the total carrying capacity of a TTU is far below that of an MTS, while on the other hand TTUs are more flexible and logistically simpler than MTSs, as not the whole journey with several pick-up and drop-off locations has to be planned. Instead, only one transfer job from a pick-up to a drop-off location is usually performed simultaneously by a TTU. The investment costs for a typical TTU add up to about 90,000 € (Saanen 2006).

AGVs (see Fig. 2.6c) are unmanned robotic transport vehicles that drive along predefined paths. The road network for AGVs is defined by electric wires or transponders in the ground, which enable accurate positioning of these vehicles (Steenken et al. 2004). This vehicle type has been widely used for many years in indoor warehouses and production facilities (Egbelu and Tanchoco 1984), before it is introduced for large-scale outdoor operations at seaport container terminals in the 1990s (Saanen 2008). Within the maritime working environment, AGVs are capable of carrying either one $40'/45'$ container or two $20'$ containers and the maximum load capacity is up to 60 t. In order to detect obstacles and to avoid collisions, the front and the back of AGVs are equipped with infrared sensors. However, if an obstacle is hit by an AGV, its engine is immediately switched off by dead man's switches at the front and the back of the AGV. In addition, the AGV-road network is subdivided into several segments in order to avoid deadlock situations and collisions. Before a certain segment of the road network is entered by an AGV, the relevant segment has to be claimed exclusively for that AGV and consequently no other AGV will be allowed to access the claimed segment (Steenken et al. 2004). Since high investment costs of about 350,000 € per piece (Saanen 2004, p. 49) are involved with AGV systems, they are more practical for high-labour-cost countries, whereas manned vehicles are preferable in countries with low labour costs. Nowadays, AGV systems are in operation, for example, at the CTA in Hamburg (Germany) and at the ECT Delta Terminal in Rotterdam (Netherlands) (Vis and de Koster 2003; Steenken et al. 2004).

The SC—also called van carrier—is a very popular active transport vehicle that is usually man-driven. It consists of a metal frame, usually eight wheels, a driver cabin, a telescopic spreader, a cable winch and an engine (see Fig. 2.6b). Due to the profile of the metal frame—that looks like a turned 'U'—the SC is able to drive across one-TEU-wide container rows. By means of the telescopic spreader, that is mounted in between the frame and is connected with a cable winch on top of the frame, the SC can lift containers that are stacked on container piles, trucks and even trains (Bruns et al. 2007). They are able to transport either one $20'$ container, one $40'$ container or even two $20'$ containers simultaneously. Due to their stacking abilities, SCs can also be classified as storage equipment that is not locally bound and may flexibly access containers in the whole terminal yard. Commonly used SCs are able to stack containers up to three or four tiers high, which means that they can move laden over two or three containers, respectively (Steenken et al. 2004). Typically, costs of around 650,000 € are involved with each additional SC (Saanen 2006).

Within the last years, some enhancements and modifications of the common SC variants have been introduced: Firstly, in 2005 an automated SC system was put into operation at the Patrick Terminal in Brisbane (Australia) (Grunow et al. 2006). These automated SCs—which are often called ALVs—stack four tiers high and are used for horizontal transport and all stacking operations (Stahlbock and Voß 2008). Secondly, some small SC variants have been introduced that only stack 1-over-1. These SCs are called shuttle carriers or sprinter carriers and may be operated man-driven or automated (Noell 2011; Kalmar 2011b). In contrast to SCs of normal height, they are not designed for stacking, but for horizontal transport only. Nevertheless, their container-lifting capabilities allow for partly decoupling of the horizontal transport from the crane operations at the quay and in the storage yard (Pirhonen 2011). In addition, due to their limited height, shuttle carriers can drive faster than SCs of normal height—in particular in curves, as they are less vulnerable to falling over (Noell 2011).

2.2.3.3 Storage Equipment

International container terminals that store containers in stacks—not on chassis—make use of different types of stacking equipment to store containers in the stacks, to move containers within the storage yard and to get them out of the stacks. The most common types of storage equipment are reachstackers, forklifts, SCs and different variants of yard cranes (Vis and de Koster 2003; Saanen 2004, p. 33). While the SC is illustrated and explained in the previous subsection, the three other types of storage equipment are schematically illustrated in Fig. 2.7.

Reachstackers (see Fig. 2.7a) and forklifts (see Fig. 2.7b) are quite similar in their appearances and their capabilities. Both are rubber-tyred vehicles that are usually powered by diesel engines and that are equipped with a driver cabin in the rear of the vehicle (Kalmar 2011a). Forklifts and reachstackers are mainly deployed in local ports that do not have larger machines like yard cranes in operation. Both vehicle types are very flexible, as they can be moved between different stacks and

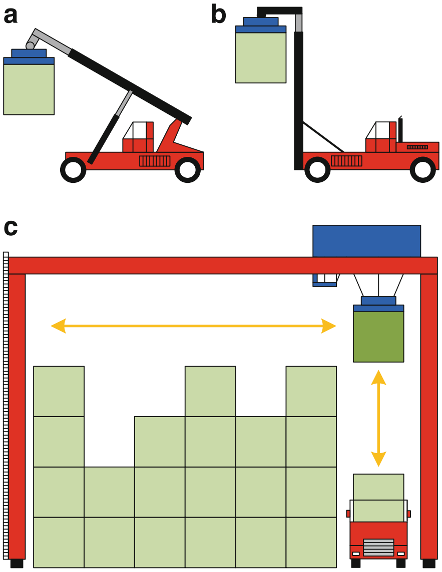


Fig. 2.7 Schematic illustration of storage equipment. (**a**) Reachstacker. (**b**) Forklift. (**c**) Yard crane

storage areas and because they can be used for both stacking and horizontal transfer of containers (Alvarez 2006; Brinkmann 2011). While investment costs of around 325,000 € may be involved with each reachstacker, the purchasing costs of a typical forklift add up to 250,000 € (Saanen 2004, p. 49).

For several reasons, forklifts are nowadays continuously replaced by modern reachstackers at stevedoring facilities and local seaport container terminals. Firstly, the spreader of reachstackers is fixed at the end of a sloped beam that is comparable to those of telescopic cranes, while the spreader of forklifts is mounted on a lifting frame. Therefore, reachstackers are able to lift containers over the outer piles of a stack and to store or retrieve them onto/from inner piles, so that even storage positions in the inside of a stack—which require a lot of shuffle moves for forklifts—may be directly accessible for reachstackers. While a reachstacker may have a dead weight of up to 100 metric tons, its lifting capacity—which may be up to 50 metric tons—depends on the outlay of the telescopic beam. Secondly, more freedom of manoeuvring with laden containers is provided by reachstackers, which allows for a more accurate container positioning. Thirdly, due to the absence of a mast, reachstackers have a better forward visibility for the driver than forklifts. Fourthly, due to the absence of a mast and the low vehicle height, reachstackers can drive into warehouses more easily (Mizunuma et al. 2005; Mietschnig 2005; Brinkmann 2011).

The most common storage equipment for larger seaport container terminals is shown in Fig. 2.7c—the yard crane. This type of storage equipment is on the one hand involved with high investments, but on the other hand high-density storage along with good productivities are provided by it. Comparable to QCs, yard cranes mainly consist of portal, trolley and spreader, which allow for easy access to each pile of a yard block (Vis and de Koster 2003). Rail cranes that are deployed for loading and discharging of trains at the rail station of a terminal are very similar. The main difference is that no yard block is located within the portal, but rail tracks (Boysen and Fliedner 2010). Several variants of yard cranes—that differ in technical and logistical attributes—are in operation at international container terminals: The portal of a yard crane can either move on rubber tyres or on rails over an entire yard block and horizontal-transport vehicles are either loaded and discharged in parallel to the yard block or at its fronts. In addition, the degree of automation, the yard-block dimensions and the number of deployed yard cranes per yard block may vary considerably. Depending on the technical specifications of a yard crane, the investment costs may be up to 2,000,000€ per crane (Saanen 2006). In Chap. 3, the logistical operations and the technical attributes of these yard-crane variants are explained, discussed and assessed in detail.

2.3 Assessment of Container Terminals

Several hundreds of seaport container terminals are in operation around the world, which differ greatly in framework conditions, appearance and performance (Watanabe 2001; Saanen 2004, pp. 34–36). Therefore, in order to allow for a substantiated and objectifiable evaluation and comparison of container terminals, dozens of indices and ratios are developed to classify and to evaluate the design and the performance of different container terminals. In this section, the most frequently used indices and ratios for the categorisation and evaluation of seaport container terminals are introduced. Firstly, the most common design indicators for classifying different types of seaport container terminals are presented. Thereafter, commonly used performance indicators for evaluating the service level and the efficiency of different container terminals are introduced.

2.3.1 Design Indicators

Container terminals can be classified by two closely linked types of indicators. Firstly, design-influencing factors greatly affect the resulting design of a container terminal in terms of equipment choice and capacities. Secondly, resulting design indicators give useful information on the main design characteristics of a container terminal and mainly depend on the design-influencing factors. The size of the QCs—as a resulting design indicator—is for example determined by the size of the calling vessels, which belongs to design-influencing factors.

The three main design indicators of container terminals are the annual terminal throughput π^{through}, the annual container-handling capacity and the storage capacity π^{sc}. The annual terminal throughput π^{through} is expressed as the number of containers that are loaded and discharged to/from sea-going vessels per year. This number is mainly determined by the location of the terminal and local economic conditions. In contrast to the terminal throughput, the annual container-handling capacity does not only take into account the realised QC moves, but also the theoretical container-handling capacity, which is expressed as TEUs per year, of the container terminal as a whole is indicated by this number. It is determined by the limiting factor of quay length, waterside-handling capacity, storage capacity, landside-handling capacity, hinterland-connection capacity and available handling equipment. Another important design indicator is the storage capacity π^{sc} of a terminal which is usually measured in TEUs and computed as the product of the number of TEU groundslots and the number of container-stacking tiers in the storage yard (Saanen 2004, pp. 36–40).

Design-influencing factors are the transshipment factor, the mean container-dwell time, the TEU-factor and various others. The transshipment factor π^{ts} gives the fraction of the annual terminal throughput π^{through} that is induced by containers that both arrive and depart by sea-going vessels. As explained in Sect. 2.1.3, different types of container terminals can be distinguished on basis of the transshipment factor. While terminals with very high transshipment factors are simply called transshipment terminals, facilities with rather small fractions of transshipment containers are termed import-export terminals. For the performance of transshipment terminals, the waterside operations, including the ship-to-shore subsystem and the waterside horizontal-transport subsystem, are of major importance, whereas the hinterland-connection subsystem with its truck and train-handling facilities is more important for import-export terminals. The storage subsystem is of great importance for both terminal types, but the waterside interface of the storage subsystem is more important for transshipment terminals, as the imbalance between waterside and landside usage of storage equipment is continuously increasing with the transshipment factor. As a rule of thumb, terminals with values of $\pi^{\mathrm{ts}} \geq 66\%$ are mostly termed as transshipment terminals, while terminals with smaller fractions of transshipment containers are usually classified as import-export terminals (Watanabe 2001; Saanen 2004, pp. 38–39).

The mean container-dwell time $\overline{\delta}$, which is discussed along with the storage function of the terminal in Sect. 2.2.1, is measured as the number of days that containers stay on average in the container-storage yard of the terminal. Usually, most containers stay a rather short period of time on the terminal—often only 1 or 2 days—while much fewer containers stay notably longer, sometimes even up to several weeks. Average dwell-time figures of container terminals usually depend on their transshipment factors. While the average dwell time of transshipment terminals is around 3–5 days, the average dwell time for import-export terminals may vary between 5–15 days (Saanen 2004, pp. 42–43). The relation between $20'$ and $40'$ containers is specified by the TEU-factor π^{teu}, which is usually given as the fraction of $40'$ containers plus one. For example, a typical value of $\pi^{\mathrm{teu}} = 1.5$ indicates that an average container is of the size of one and a half TEU, which means that half of the handled containers are $20'$ and the other half $40'$ long.

Further site-specific design-influencing factors of container terminals are draught restrictions, soil conditions, the shape of the land (width and depth) and the user-type of the terminal (dedicated or multi-user) (Saanen 2004, pp. 34–40). Firstly, the maximum vessel size in terms of loaded draft that can be served at a terminal is limited by the available draught in the port and in the access course. Secondly, the load-bearing capacity of a terminal area and along with it the stacking height and the applicable equipment types and dimensions are greatly affected by the soil conditions of the terminal. Thirdly, the used stacking and horizontal-transport equipment as well as the yard layout in terms of width, length and height are to a large extent defined by the given shape of the terminal area. Finally, several design-influencing factors like the size of the calling vessels and the transshipment factor might be influenced by the user-type of the terminal (Saanen 2004, pp. 18–21). While dedicated terminals often are subsidiaries of shipping lines and are mainly used by these shipping lines and their allied partners, multi-user terminals are usually called by vessels of several different shipping lines and/or alliances (i.e., they have multiple users) (Biebig et al. 2008, p. 228).

The storage capacity π^{scmin} that is required in order to comply with the annual terminal throughput greatly depends on the aforementioned design-influencing factors. It may be computed by

$$\pi^{\text{scmin}} = \pi^{\text{through}} \times \left(1 - \frac{\pi^{\text{ts}}}{2}\right) \times \pi^{\text{teu}} \times \frac{\bar{\delta}}{365} \times \pi^{\text{peak}}, \tag{2.1}$$

which is the product of the average storage-capacity requirements and the storage-peak factor π^{peak} (Saanen 2004, pp. 36–37). Multiplying the throughput with the mathematical term in the brackets yields the number of total stack visits per year in terms of containers. This value is usually smaller than the throughput, as each transshipment container leads to only one stack visit but two QC moves. For reasons of simplification, only import, export and transshipment container flows are considered in (2.1), whereas land-land container flows are neglected, due to being of minor importance (see Sect. 2.1.3). Multiplication with the TEU-factor yields the number of stack visits per year in terms of TEU. This number is then multiplied with the fraction of a year that containers stay on average in the yard, which yields the average storage-capacity requirements. However, for several reasons the occupancy rate of the storage capacities is not a constant value. Moreover, it is subject to terminal-dependent variations, which have to be taken into account for the storage-yard design as otherwise bottlenecks of the storage capacity will be the result from time to time. Therefore, the storage-yard design should be based on the maximum storage-capacity requirements and not the average requirements. Hence, the average storage-capacity requirements have to be multiplied by the storage-peak factor π^{peak}. First of all, hourly variations of the occupancy rate occur because usually the vessel-loading operations do not start before the discharging operations have (nearly) been finished. In addition, daily variations may be induced by the vessel-call pattern of the terminal and seasonal variations are dependent on the transshipped goods. Altogether, the greater the variations of the occupancy rate of the storage yard, the more storage capacities have to be available in order to cope with the annual terminal throughput.

2.3.2 Performance Indicators

Seaport container terminals are simultaneously faced with several restrictions and demands of their different stakeholders: Workers want security of employment, residents demand low noise and exhaust emissions, authorities require the compliance with laws, truckers are interested in short processing times and shipping lines require short, flexible and reliable turn-around times for vessels as well as low rates for loading, discharging and storage of containers. But, the final decision makers are the owners (shareholders) which are generally interested in a high shareholder value (Copeland et al. 2003, pp. 20–21). As a consequence, there are many different types of indicators for measuring the performance of seaport container terminals, of which the most common are subsequently presented. Firstly, several service-level indicators are introduced, which are related to the demands of the customers of container terminals. Thereafter, terminal and equipment-efficiency indicators are presented, which can be used to evaluate the efficiency of the whole terminal facility and the efficiencies of different types of terminal equipment. Finally, cost-efficiency indicators are discussed, which allow for cost-based comparisons of different container terminals.

2.3.2.1 Service-Level Indicators

Service-level indicators provide figures about the demands of terminal customers and the degree of fulfilment of these demands. Therefore, these indicators are of great importance for the terminal customers which include shipping lines, truckers and rail operators. Six different service-level indicators are mentioned by Saanen (2004, pp. 40–41): the maximum vessel size, the vessel-berthing time, the landside-service time, the degree of flexibility, the handling charge and the storage charge.

Along with the steadily increasing vessel size, the draught, width and height of the vessels are increasing as well. Therefore, the maximum vessel size that can call at a terminal is defined by the available draught at the quay wall and on the waterway to the terminal as well as by the size and outreach of the used QCs (see Sect. 2.1.1). For shipping lines, the capability to handle a vessel is an essential foundation for calling a certain terminal on their routes.

The time vessels stay in port is of great importance for shipping lines—in particular for deep-sea vessels—since these high investments only earn money when shipping containers at sea. Therefore, shipping lines prefer rather short vessel-berthing times, which are usually contractually defined in terms of guaranteed time windows for vessel service upon arrival (e.g., 24 h). An excess of the defined time window may result in a costly disturbance of the sail scheme of the vessel, which is usually the basis for the contractually defined time window. Altogether, the vessel-berthing times are often regarded as the most important service-level indicators of container terminals (e.g., Ng 2005; Sciomachen and Tanfani 2007; Böse 2011).

As for the shipping lines the vessel-berthing time is of great importance, the landside customers greatly focus on the service times of their equipment. The truckers and rail operators desire short service times for delivery and pick-up of containers in order to perform more transport jobs within the same period of time. In addition, the rail transport may be dependent on certain time windows for some rail routes. Thus, late train departures from the rail station of the terminal may induce even further delays for the trains due to blocking of certain rail routes. However, terminal operators usually regard shipping lines to be the more important group of customers than landside customers (Nazari 2005, p. 25).

The shipping lines are forced to demand more and more flexibility from the container terminals due to the ever-increasing trend towards JIT processes on the part of its customers (Siepermann and Krieger 2005). In this context, flexibility means that the shipping lines want to be allowed to make changes in the load plans of the vessels as late as possible and that even containers that arrive on the landside after loading has started are processed. Although more flexibility may be involved with longer vessel-berthing times or reduced equipment efficiency, the importance of flexibility is continuously increasing (Steenken et al. 2004).

Usually, container terminals yield most revenue by the handling charge that is raised from the shipping lines for each container handled by the QCs. Therefore, the handling charge is of major importance for both the business success of the terminal and its attractiveness for shipping lines. Due to different cost structures and different degrees of competition, the handling charges may vary widely between different regions. In addition, the handling charges may even vary considerably between different shipping lines, as they are based on individual contracts.

Besides the handling charge that is raised for the transshipment function of a terminal, an additional charge is usually raised per storage day of a container for its storage function. These storage-day charges and the underlying pricing system differ considerably among international container terminals because of regional differences in scarcity of land and terminal competition. For example, some terminals raise constant charges for all storage days, while the first couple of days may be free of charge at other terminals. However, the less yard space is available, the more terminal operators tend to increase the storage-day charges in order to keep the container-dwell times low.

2.3.2.2 Terminal-Efficiency Indicators

As a container terminal is a rather complex system (see Sect. 2.2.2), it is hardly possible to evaluate the performance and the efficiency of a whole container-terminal facility by a single figure. Referring to Saanen (2004, pp. 42–48), five different terminal-efficiency indicators can be distinguished: the standardised quay-wall-handling capacity, the standardised storage-handling capacity, the storage-yard fraction, the yard density and the accessibility of containers. While the first two indicators may be used to assess the transshipment function of terminals, the latter three indicators may be involved with the evaluation of its storage function.

The standardised quay-wall-handling capacity gives the theoretical annual handling capacity of a container terminal (see Sect. 2.3.1) for a standardised length of the quay wall. It is measured as annual TEU per quay wall metre and calculated by dividing the annual handling capacity of a terminal by the length of its quay wall. But the required length of the quay wall can usually not be influenced by terminal operations, moreover it is just determined by the size of the calling vessels and the vessel-call pattern of the terminal. Hence, typical figures of the standardised quay-wall-handling capacity vary greatly between 150 and 2,000 yearly $^{\mathrm{TEUs}}/_{\mathrm{m}}$. While high values may be the result of a balanced quay-wall occupation, an uneven distribution of vessel arrivals yields lower values of the standardised quay-wall-handling capacity.

The standardised storage-handling capacity is comparable to the former indicator, as it gives again the theoretical annual handling capacity of a container terminal, but here for a standardised area of the terminal. It is measured as annual TEU per hectare and yielded by dividing the annual handling capacity of a terminal by the total terminal area. Due to shorter dwell times and lower storage-area requirements of transshipment containers (see Sect. 2.3.1), it may be expected that higher values of the standardised storage-handling capacity are realised by transshipment terminals. As a rule of thumb, the values do not exceed 23,000 and 50,000 yearly $^{\mathrm{TEUs}}/_{\mathrm{ha}}$ for import-export and transshipment terminals, respectively (Watanabe 2001).

The share of the total terminal area that is used for storage of containers is given by the storage-yard fraction. Terminals are normally seeking to increase this value as far as possible without worsening other indicators in order to increase the storage capacity of the terminal, which may enable higher annual terminal throughputs. For example, the horizontal-transport area may be reduced, but possibly negative consequences for terminal operations due to traffic congestions have to be considered. Typical values of the storage-yard fraction are in the range from 0.5–0.7 to 0.6–0.8 for terminals with and without a CFS, respectively (Watanabe 2001).

The quality of the stacking operations and storage-area utilisation is indicated by the yard density, which gives the number of TEU per hectare of the container-storage yard. It is computed by dividing the on average used storage capacity π^{sc} (see Sect. 2.3.1) by the number of hectares that are used for storage of containers. In practice, the values differ greatly for different storage equipment, which is illustrated in Fig. 2.8. While storing containers on chassis yields only 250 TEUs per hectare, a storage density of up to 1,100 TEUs per hectare may be realised by usage of yard cranes (Kalmar 2011a).

Finally, the accessibility of containers in the storage yard is defined by the average number of shuffle moves required to make a certain container available to take it out of the stack to the the horizontal transport. This indicator is of great importance for the annual handling capacity of a container terminal, because a better accessibility and fewer shuffle moves are involved with a higher productivity of the terminal equipment (see Sect. 2.3.2.3). Storing containers on chassis or stacking just one tier high yield the best possible accessibility, as each container is directly retrievable. In contrast, a rather bad accessibility is usually yielded by

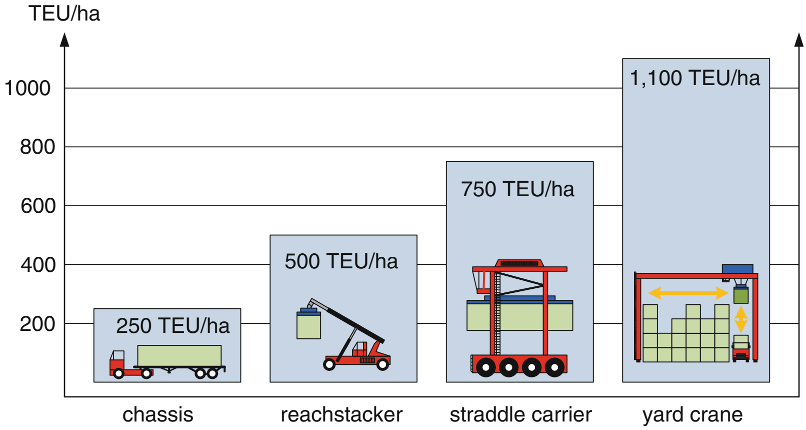


Fig. 2.8 Storage-equipment-dependent yard density (based on Kalmar 2011a)

stacking several TEU high, as not each container might be directly accessible. The accessibility is determined by the stacking height in the storage yard and the knowledge of the sequence in which containers are retrieved from the stacks. On the one hand, a reduction of the stacking height would improve the accessibility, while on the other hand the yard density would decrease, which means, there is a trade-off between both indicators (De Castilho and Daganzo 1993; Kim et al. 2008). Knowledge about the container-retrieval sequence at the waterside interface of the container-storage yard depends on the quality of the available information about the stowage plans. In case the stowage plans are timely available and reliable, the containers may be stacked in the order they are needed at the QCs such that shuffle moves are reduced. However, in real life this assumption will often not hold, as shipping lines demand more flexibility of the terminals concerning the stowage plans (see Sect. 2.3.2.1).

2.3.2.3 Equipment-Efficiency Indicators

The efficient usage of all kinds of terminal equipment is indicated by the corresponding equipment productivity, which is usually given as the number of containers that are handled by the relevant equipment per hour. The equipment productivity can be measured for each type of terminal equipment, like QCs, SCs, TTUs, AGVs, reachstackers, yard cranes and rail cranes. In practice, typical productivity figures vary greatly with the regarded type of terminal equipment as well as with the specific kind of productivity measure. In fact, the following four different kinds of equipment-productivity measures can be distinguished: technical productivity, operational productivity, net productivity and gross productivity (Saanen 2004, pp. 44–47).

The technical equipment productivity is defined as the theoretically maximum possible number of handled containers per hour. All kind of disturbances like interferences with other equipment, stochastics of manual operations and further external influences are neglected. Moreover, the technical productivity is only based on 100% reliable technical figures like driving distances, accelerations and velocities. In contrast, the operational and net productivities of terminal equipment take into account delays due to drivers and other external influences (e.g., weather conditions). But while the operational productivity assumes at least ideal circumstances for all other terminal equipment, such that no delays due to interferences or waiting times with other equipment occur, these disturbances are explicitly considered by the net productivity. Finally, the gross productivity is measured over longer periods of time (e.g., day, vessel-operation time).Therefore, additional disturbances of the equipment operations like meal breaks, shift changes and machine breakdowns are grasped as well. These disturbances, which are not inherent to regular operations, are not observed by the former three productivity measures. Altogether, the relation between these four productivity measures is described by:

$$\text{technical} > \text{operational} > \text{net} > \text{gross}. \tag{2.2}$$

In practice, terminal operators are mostly seeking for improvements of net or gross productivities, as the operational reality is best represented by these figures. Vessel-berthing times and decisions on the number of required equipment are determined by these productivities and changes in technical as well as operational productivities will be reflected by the net and gross productivities as well. As a consequence, most productivities are given as net or gross values.

The probably most popular equipment productivity measure is the GCR (gross crane rate), which gives the gross productivity of QCs (Petering et al. 2009; Goussiatiner 2009). It is defined as the average number of containers that are loaded and discharged by a single crane per allocated crane hour, which is consistent with the general definition of gross productivities, as not any kind of disturbances during QC operations is excluded from the allocated crane time (Goussiatiner 2009). The GCR is often regarded as the most important performance indicator of seaport container terminals for both the shipping lines and the terminal operators themselves (Goussiatiner 2009). Firstly, due to its inverse relation with the vessel-berthing time, the GCR directly affects the turn-around times of vessels, which is of particular importance for shipping lines (see Sect. 2.3.2.1). Secondly, terminal operators may use the GCR as a benchmark on the efficiency of the overall terminal operations, since most terminal operation either originate from or terminate at the QCs. Therefore, the GCR is either directly or indirectly affected by efficiency changes of other terminal equipment (e.g., yard cranes or AGVs). As a consequence, the GCR depends on numerous factors, like for example crane speed, lifting capacity, spreader type, wind conditions, driver skills, delays in horizontal transport, delays in storage-yard operations and various others. A detailed discussion of these factors influencing the GCR is given by Goussiatiner (2009).

Two less popular efficiency indicators for QCs are the QC-throughput index and the QC-density index. Usually, the QC-throughput index is used as a rule-of-thumb-based indicator on the appropriateness of the number of deployed QCs in relation to the throughput of the terminal. It is computed by dividing the annual terminal throughput π^{through} by the number of deployed QCs. Nowadays, the latest QC technologies allow for reasonable values of the QC-throughput index in the region of 100,000 containers per QC. However, substantially lower values may indicate rather inefficient terminal operations, whereas higher values may indicate the possibility to increase the annual terminal throughput by deploying additional QCs (Saanen 2004, p. 45).

The average length of a QC operation zone is represented by the QC-density index, which is computed by dividing the length of the quay wall that is equipped with rails by the number of QCs. Typical values of this index are greater than 100 m per QC, only some Asian terminals have smaller QC densities. Furthermore, usually higher values are observed for import-export terminals than for transshipment terminals. Comparatively high values of this index may indicate (cost-) inefficient operations due to an oversized quay wall and longer driving times of horizontal-transport machines. Whereas comparatively low values may indicate inefficient operations due to heavy congestions of horizontal-transport machines at the QCs (Saanen 2004, p. 47).

2.3.2.4 Cost-Efficiency Indicators

Finally, terminal operators do not seek for improvements of terminal and equipment efficiency for reasons of self purpose. Moreover, at least privately owned container terminals are generally striving for high long term profits, since, like for most companies, the overall business objective is the maximisation of the shareholder value. Therefore, terminal operators strive for increases of the annual terminal throughput and the profit margin per handled container. While the profit margin is directly determined by the expenses of the terminal, also the terminal throughput is indirectly affected by the terminal costs, since the possibility for handling-charge reductions in order to attract additional throughput without worsening the profit margin is greatly dependent on the cost situation of a terminal. As a consequence, the costs of seaport container terminals are of major importance for their competitiveness and the resulting shareholder value (Copeland et al. 2003, pp. 22–23).

Cost-efficiency indicators allow a comparison and assessment of the cost situation of a terminal. The most familiar indicator is the container-cost index, which indicates the average costs that are involved with the handling of a single container. It is computed by dividing the total costs of a terminal per year by its annual throughput π^{through}. However, different cost categories can be distinguished. Thus, different variants of the container-cost index exist as well. First of all, it can be distinguished between the yearly operating and the initial investment costs. The investment costs mainly consist of investments in facilities (e.g., quay walls, pavings, buildings) as well as purchasing costs for terminal equipment (e.g., QCs, SCs, AGVs) and required software products (e.g., TOS—terminal-operating system). Depending on the dimensions and the technical equipment of a container terminal, the investment costs may sum up to several 100 million Euros (Saanen 2004, pp. 48–50).

In form of capital costs for both debt capital and equity, these investment costs may be implicitly taken into account within the operating costs as interest payments and opportunity costs. In addition, the operating costs consist of labour costs, material costs (e.g., spare parts, fuel, energy), service costs (e.g., lashing, maintenance, administration) and lease costs (e.g., land, quay walls). Thereof, the labour costs make up for the biggest part. Of course, due to local wage rates, union power and other historical factors, labour costs vary notably between different ports and countries. Depending on the location of a terminal, the fraction of the labour costs may vary between 35% (East Asia) towards 50% (Northwest Europe) and 65% (US West coast). The labour costs for a Northwest European container terminal vary in the range from 30 to 38 Euro per TEU. As a consequence, a reduction of workforce by automated terminal equipment may offer remarkable savings of labour costs. However, the comparatively high investment costs of these equipment types only pay off for terminals with rather high fractions of labour costs, as otherwise the cost savings are outbalanced by additional capital costs (Saanen 2004, pp. 49–50).

2.4 Classification of Terminal-Planning Problems

In the 1990s, only little attention was given to the area of container logistics by the OR (operations research) community, but due to its societal importance it has gained a lot of attention in the last years (Meersmans 2002, p. 27). Several hundreds of OR articles and other scientific sources are available today that deal with problems of the container logistics sector—in particular with planning problems of seaport container terminals. The most recent comprehensive literature survey on container-terminal logistics is presented by Stahlbock and Voß (2008). Further overviews are provided by Meersmans and Dekker (2001), Vis and de Koster (2003), Steenken et al. (2004), and Günther (2005).

In this section, the most popular terminal-planning problems are introduced and an overview on selected OR models and methods is given in order to clarify the application of OR methodologies in this area. Firstly, a classification of planning and decision problems that arise in the context of seaport container terminals is provided. Secondly, problems and selected methods concerning terminal-design planning are roughly dealt with. Thereafter, the most important operational planning problems are discussed in detail.

2.4.1 Classification of Decision Problems

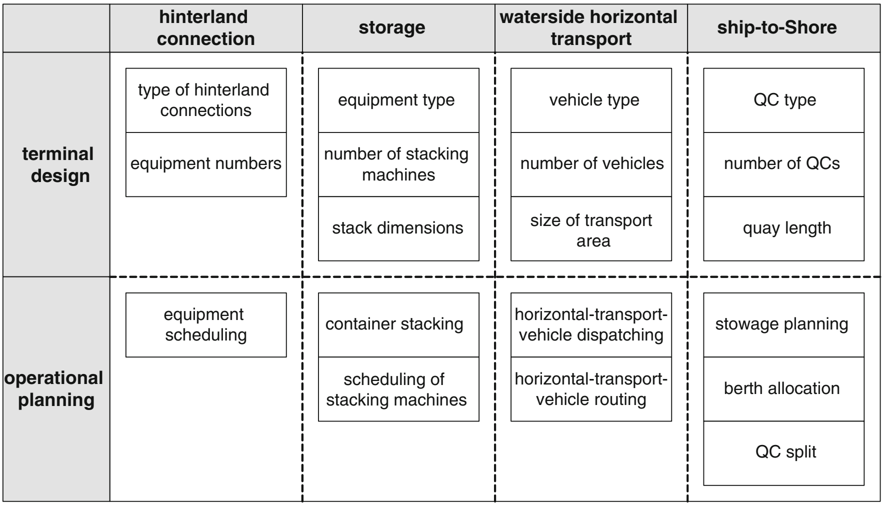
Numerous planning and decision problems arise in the context of seaport container terminals that differ with respect to the hierarchical level involved and the terminal subsystem affected. Therefore, decision problems are often classified into several groups of planning problems. In Meersmans and Dekker (2001), decisions are classified according to the hierarchical level involved only. It is distinguished between the strategical, tactical, operational and real-time decision level. Decisions on the strategical level deal with the design of container terminals in terms of layout and equipment types. The tactical level concerns decisions on terminal structures that can be implemented within several weeks or months (e.g., numbers of equipment and employees). On the operational level, the daily and hourly available capacities in terms of workforce and equipment are allocated to the actual work. Finally, decisions on the real-time level deal with quite short-termed problems, which have to be decided within a few seconds or minutes (e.g., routing of vehicles).

Another classification scheme for terminal decision problems is proposed by Günther and Kim (2006). In addition to Meersmans and Dekker (2001), the decision problems are not only categorised according to the hierarchical level involved, moreover, the concerned planning object (e.g., AGVs, storage yard, QCs) is also used as a classification criterion. Contrary to Meersmans and Dekker (2001), Günther and Kim (2006) distinguish only three decision levels: the terminal-design level, the operational planning level and the real-time control level. The design level comprises all former strategical decisions as well as parts of the former tactical decisions (e.g., numbers of equipment), while the operative level consists of most of the former tactical decisions. Finally, the real-time level of Günther and Kim (2006) combines the operational and the real-time level of Meersmans and Dekker (2001).

Here, a modified classification scheme is introduced which—comparable to that of Günther and Kim (2006)—categorises decision problems according to the involved hierarchical level as well as the related subsystem of the terminal. The detailed classification scheme is shown in Fig. 2.9. Different from Meersmans and Dekker (2001) and Günther and Kim (2006), only the terminal-design level and the operational planning level are distinguished here for the categorisation according to the hierarchical level of a decision problem. While the terminal-design level is identical to that of Günther and Kim (2006), the operational planning level combines both the former operative and real-time levels. Altogether, each decision problem that is associated with one of the four terminal subsystems (see Sect. 2.2.2) is either categorised to be a terminal-design or operational planning problem.

2.4.2 *Terminal-Design-Planning Problems*

In general, the terminal-design level comprises all kinds of decisions on the layout and the choice of equipment of seaport container terminals (see Fig. 2.9). These decisions are usually made by terminal planners during the initial planning phase of a completely new terminal facility, an expansion of an existing terminal or a conversion of an existing terminal (Böse 2011). Usually, the decisions are made with respect to technical feasibility, economic profitability and operational performance (Günther and Kim 2006). The decisions on type and number of terminal equipment as well as terminal layout usually involve investments of several million Euros, which cannot be changed easily within short time horizons of only several months.



	hinterland connection	storage	waterside horizontal transport	ship-to-Shore
terminal design	type of hinterland connections equipment numbers	equipment type number of stacking machines stack dimensions	vehicle type number of vehicles size of transport area	QC type number of QCs quay length
operational planning	equipment scheduling	container stacking scheduling of stacking machines	horizontal-transport-vehicle dispatching horizontal-transport-vehicle routing	stowage planning berth allocation QC split

Fig. 2.9 Classification of decision problems

In general, building up new terminals (including civil and structural engineering) may take some years and only pays off after 10–15 years of operating time. Once the civil engineering of a terminal is completed, decisions on both the equipment types and the logistical terminal operations are usually more or less fixed for the next decades. Due to long-winded delivery times, even the numbers of certain terminal equipment cannot be changed within a few months. Altogether, the effects of the decisions that belong to the design level are characterised by rather long-ranging validity and huge investments.

For the ship-to-shore subsystem, mainly three decisions have to be made on the terminal-design level: the QC type, the number of required QCs and the length of the quay wall have to be determined (Böse 2011). The decision on the QC type consists of some detailed questions concerning the outreach and the clearance of the planned QCs as well as their trolley (i.e., single or double) and spreader technologies (i.e., single, twin or tandem) (see Sect. 2.2.3.1). In order to save costs, terminal operators initially try to minimise the length of the quay wall and the number of QCs in such a way that the planned annual terminal throughput or certain performance indicators (see Sect. 2.3.2) can just be met with respect to some external input (e.g., vessel-call pattern). For that purpose, a mathematical optimisation model is proposed by Meisel and Bierwirth (2011) to determine the optimal number of QCs with respect to cost and performance aspects for a terminal with given length of the quay wall, while Hartmann et al. (2011) present a simulation model to verify both the planned length of the quay wall and the planned number of QCs.

For the waterside horizontal-transport subsystem, the design level comprises decisions on the vehicle type that should be used for horizontal transport, the required number of these vehicles and the dimension of the corresponding driving area (Böse 2011). The vehicle type that is used for horizontal transport may either be AGV, ALV, MTS, SC or TTU (see Sect. 2.2.3.2). By means of a simulation study, the usage of AGVs, TTUs and ALVs is evaluated by Duinkerken et al. (2006) in terms of cost and performance indicators for a realistic scenario of the Maasvlakte terminal in Rotterdam (Netherlands). Another simulation-based performance evaluation is presented by Yang et al. (2004), who compare the alternative deployment of AGVs and ALVs. One interesting finding is that savings in the number of required transport vehicles can be realised by the usage of ALVs instead of AGVs. Due to being interested in cost savings, terminal operators usually try to minimise the number of transport vehicles with respect to the desired annual container-handling capacity. While a system to determine the necessary number of SCs is provided by Steenken (1992), Vis et al. (2001) present a polynomial-time algorithm to determine the number of AGVs required at a semi-automated container terminal. Finally, in order to optimise the storage-yard fraction, terminal operators are often seeking to minimise the dimensions of the driving area with respect to certain safety distances between passing vehicles and required manoeuvring space at the quay cranes and in the storage yard. In order to do so, Ranau (2011) presents a planning approach for the optimal dimensioning of the driving area for automated horizontal-transport systems and compares the space requirements of AGVs and ALVs.

Comparable to the horizontal-transport subsystem, the following decisions have to be made on the design level of the storage subsystem: the equipment type that should be used in the storage yard, the required number of these machines and the layout of the storage yard (Böse 2011). Mainly four types of storage equipment can be distinguished, namely SCs, yard cranes, forklifts and reachstackers (see Sect. 2.2.3.3), whereof only the first two types are commonly used at bigger seaport container terminals. In addition, several technically and logistically different variants of yard cranes are available that are explained in detail in Chap. 3. Both the decisions about the required number of storage machines as well as the decision about the layout of the storage yard heavily depend on the selected equipment type. However, in order to yield good results in terms of cost and performance indicators, terminal planners usually try to minimise the number of storage machines and the storage area with respect to the storage capacity π^{scmin} that is required to achieve the intended container-handling capacity. The decision on the layout of the storage yard does not only concern its space requirements, moreover also the arrangement of yard blocks as well as the length, width and stacking height of these blocks have to be determined.

Numerous authors have investigated the design-planning problem of the storage subsystem at seaport container terminals—in particular for different kinds of yard-crane systems. A comprehensive overview on this literature is provided in Chap. 4 of this work, where the selection of stacking equipment and the layout planning of the container-storage yard are addressed in great detail for a special type of gantry-crane system: the RMGC system.

Finally, on the design level of the hinterland-connection subsystem it has to be decided on the required types of hinterland connections and the equipment of the corresponding facilities (Böse 2011). While no hinterland connection is required for pure transshipment terminals, for all other terminals a hinterland connection for XTs, trains and/or barges has to be implemented. For all types of hinterland connections, it has to be decided on the type and number of equipment that should be used for loading and discharging of the corresponding modes of transportation. In addition, the gate capacities have to be defined for the hinterland connection by XT and the number and length of rail tracks on the rail station need to be defined for the hinterland connection by train.

2.4.3 Operational Terminal-Planning Problems

In this subsection, an overview on some of the most popular operational planning problems of seaport container terminals is given. Decisions on the sequences in which transport tasks are executed by the horizontal-transport equipment may, for instance, lead to an improvement of the gross productivity of these machines (see Sect. 2.3.2.3), which then allows for reduction of the number of transport vehicles needed and, along with it, a reduction of the container-cost index (see Sect. 2.3.2.4). Therefore, the performance of seaport container terminals and several decisions on the terminal-design level are greatly influenced by these operational planning decisions.

Because of its relevance to most operational terminal-planning problems, there is a need to discuss the special planning situation of online optimisation which is characterised by uncertain and incomplete planning information. This is carried out in the first subsection. Thereafter, the problems as well as related models and methods are presented for decisions on stowage planning, berth allocation, QC split, horizontal-transport-vehicle dispatching, horizontal-transport-vehicle routing, container stacking and scheduling of stacking machines.

2.4.3.1 Online Optimisation

In classical optimisation, which is here referred to as offline optimisation, it is assumed that all input data of an instance is known before the application of solution methods. But since in many applications decisions have to be made based on incomplete or uncertain information, this assumption is not realistic. In fact, it may be necessary to decide on a part of the total problem while new data of the problem still arrive. Such planning situations are termed online. An algorithm runs online if decisions are made whenever a new piece of data demands an action (Ascheuer et al. 1998). In addition, real-world applications often require decisions to be made within very tight time frames, which means that the problems have to be solved in real-time. Introductions and overviews to the field of online optimisation are given, for instance, by Ascheuer et al. (1998), Fiat and Woeginger (1998) as well as Grötschel et al. (2001).

Obviously, the solution quality of online algorithms cannot be expected to be as good as that of omniscient offline algorithms. Since the online algorithm has to compute the pieces of solutions before the complete problem set is known, some pieces of the solution computed will turn out to be suboptimal after the complete set of data is available. Applying an offline algorithm to the same data set after all information is available, will therefore lead to an optimal decision which cannot be worse than the online solution. But since this is not possible for online situations, special online algorithms have to be applied. Independently of the precise planning problem, the following concepts can be distinguished for the general design of online algorithms (Grötschel et al. 2001):

FIFO: The FIFO (first-in-first-out) strategy strictly serves requests in order of appearance. Efficiency issues are not regarded.

Greedy: A greedy algorithm serves that request next which leads to least cost with respect to the current system state and the corresponding objective (i.e., the algorithm acts greedily).

Replan: A replan algorithm computes an (near) optimal solution at a specific point in time. Every time some new piece of data is available, a new optimal solution is computed. All schedules made beforehand are replanned.

Ignore: An ignore algorithm computes (near) optimal solutions at a specific point in time, but the schedule made is executed and not replanned. When the current schedule is finished a new one is computed for the new requests which have become available in the meantime.

The concept of online optimisation is of great relevance to the field of container terminals, since most operational planning problems have to be regarded as online situations (Stahlbock and Voß 2010). To a large extent, the daily terminal operations are dependent on external processes like the arrival of ships, trucks and trains. None of them is very predictable. While the planned arrival times of vessels may not be met due to bad weather or delayed departure in the previous port, the arrival times of XTs are even more—almost completely—unpredictable. Besides these external processes, also the internal operations give raise to some degree of uncertainty. While the driving times and, along with them, the performance of QCs, SCs and other manual terminal equipment are somehow uncertain due to the drivers' skills, the operations of automated equipment may be disturbed by machine breakdowns. Furthermore, some dynamic events like queues at the QCs or yard cranes as well as traffic jams of the horizontal-transport machines cannot be completely predicted, as container terminals are complex facilities with several types and numbers of equipment in several dozens of possible states that can be located in a large number of yard locations (Saanen 2011). Altogether, decisions made far in advance of the actual operation may turn out to be sub-optimal by the time that decision is realised, because the planning situations of most operative problems are continuously changing due to imperfect and uncertain data. Therefore, most operational terminal-planning problems are amenable to online optimisation methods.

2.4.3.2 Stowage Planning

In former times, stowage plans (see Sect. 2.2.2.2) were created by the captain of the relevant vessel (Sciomachen and Tanfani 2007), but nowadays the creation of stowage plans is a two-step process. Firstly, a rough stowage plan is created by the shipping line that considers stowage positions on the vessel for all containers that are loaded and discharged during the journey of a vessel. But the containers that are planned at this process step are no precisely specified containers that can be identified by an ID. Moreover, containers are only assigned to positions according to their attributes in terms of type (e.g., standard dry, reefer), size (20′, 40′), weight and PoD (port of destination). Thus, containers having exactly the same attributes (i.e., they belong to the same category) are still exchangeable in the stowage plan at this process step. Usually, the stowage plans of shipping lines are created with the objectives to minimise the number of required QC-shuffle moves in the ports along the route of a vessel and to maximise the utilisation of the vessels, with respect to some constraints on the stability of the vessel (Steenken et al. 2004).

Secondly, based on the rough stowage plan of the shipping line, that only assigns container categories to stowage positions on the vessel, the ship planners of the container terminal create a more precise stowage plan with specific containers that can be identified by unique IDs. All attributes of a container that has to be loaded onto the vessel have to match exactly the category of the assigned stowage position on the vessel. Usually, the objective of the ship planners is the minimisation of the number of required shuffle moves in the container-storage yard, that is induced by the stowage plan due to planning a container to be loaded onto the vessel prior to another container that is stored on top of the firstly needed container (Steenken et al. 2004).

Although stowage plans are usually created offline by the ship planners (i.e., before the actual loading process of a relevant vessel has started), the underlying planning situation of vessel-loading operations is best suited for online optimisation due to several reasons (Steenken et al. 2004). However, if online stowage planning is applied by the ship planners, no specific container will be assigned to a position on the vessel in advance of the loading process. Instead, a container in the storage yard is selected that matches the required attributes and that seems to be most appropriate in terms of required shuffle moves and estimated arrival time at the relevant QC only shortly before a container of a certain category has to be loaded onto the vessel. As a consequence, a precise stowage plan is created successively and simultaneously with the actual vessel-loading process (Dekker et al. 2006).

The stowage-planning problem has been widely studied in the OR literature. Wilson and Roach (1999) as well as Wilson et al. (2001) split up a special type of the stowage-planning problem that is denoted as MBPP (master bay-plan problem) into a strategical and a tactical level. They apply local-search algorithms and techniques based on combinatorial optimisation. A similar three-phase algorithm is presented by Ambrosino et al. (2006). Sciomachen and Tanfani (2003) as well as Sciomachen and Tanfani (2007) utilise the relation between the 3D-BPP (three-dimensional bin-packing problem) and the MBPP. While Sciomachen and Tanfani (2003) aim at the minimisation of the vessel-loading time, Sciomachen and Tanfani (2007) try to maximise the net productivity of the QCs by means of a heuristic.

2.4.3.3 Berth Allocation

At large international container terminals several dozens of vessels arrive per week that all have to moor at the quay wall of the terminal. The berthing capacity is limited by the length of the quay wall. The berth-allocation problem is to assign all vessels to certain sections of the quay wall taking into account the corresponding vessel lengths and service times such that there is no overlap in the assigned sections at any point in time. The berth-allocation problem can either be treated as a discrete or continuous case. In the discrete case, only a finite number of berthing places is available (e.g., berth 1: 0–250 m; berth 2: 250–550 m, . . .), whereas, in the continuous case, a vessel can berth anywhere along the quay (e.g., between 200 and 450 m). While the arrivals of deep-sea vessels are usually known several months in advance, which allows for a far-sighted planning of the berth allocation, the arrivals of feeder vessels are only known shortly before the actual arrival at the quay (Steenken et al. 2004).

In general, the decisions on the berth allocation are mainly made with the objectives to minimise the anchoring time of the vessels before berthing at the quay is possible and to maximise the equipment productivity of the terminal. It is often tried to facilitate the latter objective by assigning berthing places relatively close to the yard area where most containers are stacked that are planned for loading onto the relevant vessel. Thus, driving times for the horizontal-transport equipment are reduced, equipment productivity is improved and the vessel-berthing time may be reduced as well (Meersmans and Dekker 2001). But decisions on the berth allocation have to take into account the technical requirements of vessels and the technical restrictions of the berthing places. Usually, not all vessels can be served at each berthing place due to limited outreach or clearance of the corresponding QCs or insufficient draught at the berthing place (Steenken et al. 2004). In addition, the number of available QCs for the berthing places should be considered for the decisions about the berth allocation, as the vessel-berthing time—and along with it the time the berth becomes available for the next vessel—is directly affected by the number of deployed QCs.

Many authors have studied the berth-allocation problem. Wang and Lim (2007) transform the berth-allocation problem into a multiple-stage decision-making procedure that is solved by means of a stochastic beam-search algorithm. A performance comparison with an approach from Dai et al. (2008) shows that the proposed algorithm is more accurate and efficient than both the state-of-the-art meta-heuristic and the traditional deterministic beam search. A TS (tabu search) algorithm for the berth-allocation problem with the objective to minimise the vessel-berthing time is presented by Cordeau et al. (2005). Furthermore, a simulation model for evaluating different berth-allocation policies is presented by Henesey et al. (2004).

2.4.3.4 Quay-Crane Split

Subsequent to the berth allocation of arriving vessels, the decisions have to be made which QCs should be used for loading and discharging these individual vessels. But this decision problem, that is termed QC-split problem, does not only comprise the allocation of QCs to vessels, moreover the QCs have to be assigned to individual bays of the vessel (Vis and de Koster 2003). In general, the number of cranes that can be deployed for a certain vessel is restricted by two factors. Firstly, not every crane can be driven to each berthing place, due to being fixed to rails. Secondly, usually terminals are historically grown facilities with QCs of different sizes, of which not all are operable for the largest vessels.

In contrast to other operational planning problems, there is no universal objective for the QC-split problem. Moreover, several situation and terminal-dependent objectives exist, like balancing the QC utilisation, minimising the sum off all delays in relation to the contractually agreed vessel-berthing times for all vessels or minimising the vessel-berthing time for an individual vessel (Steenken et al. 2004). For example, Kim and Park (2004) propose a B&B (branch-and-bound) algorithm and a greedy randomised adaptive-search procedure for the QC-split problem with the objective to minimise the weighted sum of the makespan of a vessel and the total completion time of all QCs. Whereas an early work of Daganzo (1989) provides an MIP model with the objective to minimise the sum of all delays. The assumptions are rather unrealistic (e.g., unlimited length of the quay wall), but the model can be solved exactly for small instances. In addition, Lee et al. (2008) present an MIP model with the objective of minimising the makespan for a single vessel. They propose a GA that produces near optimal solutions of the MIP model.

In addition to the berth allocation and QC split, it has to be decided on the QC mode that defines the sequence in which containers are loaded and discharged by a QC. Mainly four different modes have to be distinguished, as bays can be loaded either horizontally or vertically and it can be started either from the quay or the waterside. Altogether, the exact loading sequence of each individual QC is defined by the decisions on the relevant stowage plan, on the QC split and on the QC mode (Steenken et al. 2004).

2.4.3.5 Horizontal-Transport-Vehicle Dispatching

At international seaport container terminals, several QCs simultaneously load and discharge different vessels with a gross productivity in the range of 22–30 containers per hour (see Sect. 2.2.3.1). As a consequence, some hundreds of containers have to be transported per operating hour by the horizontal-transport vehicles between the quay and the container-storage yard. During the discharging operation of a vessel, the relevant containers have to be transferred from the quay to the storage area and vice versa for the loading operations. The corresponding transport jobs are termed import and export jobs, respectively. Each of these transport jobs has to be performed by one of several dozens horizontal-transport vehicles that are usually in operation at large container terminals. Therefore, decisions have to be made about the vehicle assignment and the sequencing of transport jobs (i.e., which vehicle performs which transport jobs in which sequence). This so-called vehicle-dispatching problem is more or less a combinatorial assignment problem. But in practice not hundreds of jobs have to be allocated simultaneously, moreover, because of the online character of container terminals (see Sect. 2.4.3.1), only some transport jobs that occur in the next few minutes are usually classified as plannable. In fact, changes in the stowage plans and inaccurate estimates of vehicle-driving times lead to frequent changes in the planning data and to a rather short planning horizon that requires frequent replanning (Steenken et al. 2004).

Like for most operational planning problems, the superior objectives of the vehicle-dispatching problem are the minimisation of the vessel-berthing time and the maximisation of the GCR with a given number of terminal equipment. But these objectives cannot be used directly as an objective function for the vehicle-dispatching problem. In fact, different operative objectives may be formulated to achieve the superior goals, such as minimisation of the QC-waiting time due to late arrivals of transport vehicles, minimisation of vehicle-waiting time at the QCs and yard blocks due to early arrivals, minimisation of total empty-driving times of vehicles and minimisation of vehicle congestion due to uneven vehicle distributions among QCs and yard blocks (Briskorn et al. 2006). Of course, the superior objectives may also be facilitated by terminal-design decisions on enhancing the number and the velocities of the vehicles. But as additional costs and congestions are provoked by such measures, operational planning decisions should usually be the first choice of the terminal operators for reaching the superior objectives.

However, the exact configuration of an objective function depends on several factors, like the lifting capability of the selected equipment type, the applied QC-allocation scheme and the deployed transport cycle mode (see Sect. 2.2.2.3). For instance, by using SCs instead of TTUs or AGVs, the horizontal transport may be partly decoupled from the QC and storage operations, which may lead to a higher importance of EDT (empty-driving time) compared to late and early vehicle arrivals. In addition, only little potential for optimisation is available when applying the dedicated allocation scheme and vehicles are operated in the single-cycle mode. The highest potential for optimisation occurs for multi-load vehicles that are operated in a pooled allocation scheme (Steenken et al. 2004).

Numerous authors have investigated the vehicle-dispatching problem—mainly for either SCs or AGVs. Kozan and Preston (1999) as well as Böse et al. (2000) look at the problem of optimising container transfers with SCs by means of GAs. While Böse et al. (2000) aim at minimising late arrivals of SCs at the QCs, the objective of Kozan and Preston (1999) is the minimisation of the vessel-berthing time. In addition, Das and Spasovic (2003) present an assignment algorithm for SCs that is shown to be superior over two alternative methods by means of a simulation study. An extensive overview on research in the design and control of AGV systems, comprising OR methods such as mathematical programming, queueing theory, network models and heuristics, is provided by Vis (2006b). Briskorn et al. (2006) propose an AGV-assignment algorithm that is based on a rough analogy to inventory management. It is shown by means of a simulation study that this formulation is superior to standard earliness-tardiness formulations. Dispatching of multi-load AGVs by means of MIP models and priority rules is dealt with by Grunow et al. (2004a,b). It is shown that performance improvements are yielded by using the multi-load mode.

2.4.3.6 Horizontal-Transport-Vehicle Routing

On a more detailed level, decisions about the exact driving behaviour have to be made for the horizontal-transport vehicles. In detail, for each drive of a horizontal-transport vehicle, a certain path has to be selected towards its destination. In addition, interferences of different transport vehicles should be solved in such a way that collisions and deadlocks are avoided. For instance, at crossings, one vehicle has to be granted the right of way, while the other vehicle has to wait. Further decisions on the driving behaviour concern the locations for space extensive turns and the shunting positions, where vehicles can wait for new transport jobs. Altogether, these decisions may be subsumed under the heading of the horizontal-transport-vehicle-routing problem. However, for manned vehicles like TTUs and SCs, all these decisions are made by the driver on a real-time level. Therefore, no control systems or algorithms are required for these vehicle types. But for automated vehicles like AGVs and ALVs, decision rules and algorithms have to be implemented, which allow for short and collision-free driving times between different locations (Meersmans and Dekker 2001).

Until today, only few authors have published works that are directly devoted to the transport-vehicle-routing problem at container terminals. In contrast to the central AGV control system that is deployed at the ECT Delta Terminal in Rotterdam (Netherlands), Evers and Koppers (1996) propose a distributed control system using a hierarchical system of semaphores, which offers more flexibility and requires less communication to control the AGVs than centralised systems. Stenzel (2008) models the AGV-routing problem as time-expanded graphs and presents different algorithms to solve this problem formulation. Further simulation studies that investigate the routing of horizontal-transport vehicles are conducted by Duinkerken and Ottjes (2000).

2.4.3.7 Container Stacking

Usually, each container that is handled at a seaport container terminal is temporarily stored in the storage yard of the terminal. The container-stacking problem deals with the question where to place containers in the storage yard that arrive at the interfaces of the storage yard or need to be relocated inside the storage yard. As a storage yard is usually subdivided into several blocks, for each container, the stacking problem consists of the choice of the yard block as well as positioning that container within the chosen yard block. A decision about the prospective position of a container in the storage yard is then addressed by the numbers of the block, the bay, the row and the tier (Steenken et al. 2004). The quality of the stacking decisions is in most cases measured in terms of the accessibility of containers in the storage yard (see Sect. 2.3.2). But due to growing container volumes and scarce land resources, it is often decided on the terminal-design level to improve the yard density by increasing the stacking height of the yard blocks, which normally leads to additional shuffle moves. However, the trade-off between the conflicting objectives of maximising the yard density and minimising the number of shuffle moves may be mitigated by stacking approaches which make use of the available information on the future container-retrieval sequence. Altogether, the minimisation of the average number of required shuffle moves for a given yard layout is often regarded as the main objective for the container-stacking problem (Dekker et al. 2006; Kang et al. 2006a,b).

In addition, there does not exist a basic stacking problem, moreover the structure of the container-stacking problem depends on several terminal-specific factors, which are mostly decided on the terminal-design level. Firstly, the stacking problem differs depending on the flow direction of the container, since usually more information on the expected retrieval times are available for containers that are planned to depart by deep-sea vessel than for containers departing by feeder vessel or XT. Secondly, different stacking problems result from different approaches of organising the yard area. While some terminals firstly stack containers in a rough pile and reposition them later to a marshalling area according to the sequence in which they are needed, other terminals stack the containers in different yard zones, that may be reserved for certain vessels or berthing places, without repositioning them later. Thirdly, the stacking problem may also differ depending on the deployed stacking equipment (Steenken et al. 2004).

Numerous authors have investigated different types of the container-stacking problem—mostly for container yards with gantry-crane systems. A comprehensive overview on this literature is for instance provided by Caserta et al. (2011). In Sect. 5.2 of this work, the container-stacking problem for container-storage yards with RMGC systems is addressed in great detail and the literature relevant to that operational terminal-planning problem is summarised.

2.4.3.8 Storage-Machine Scheduling

After the stacking problem has been solved and a storage position has been chosen for a container, it has to be decided which storage machine transports the container to its designated pile and at what time this transport job takes place. These two decisions, which are the machine-assignment and transport-job-sequencing decisions, respectively, are combined to the storage-machine-scheduling problem. Comparable to the stacking problem, a much more detailed description of the scheduling problem for container-storage yards with RMGC systems together with a comprehensive review of the relevant literature are provided in Sect. 5.3, while the scheduling problem for storage machines in general is only briefly introduced in this subsection.

All types of transport jobs have an origin and a destination, which are positions where the corresponding container is picked up and where it is placed by the used storage machine, respectively. Mainly three types of jobs have to be scheduled: storage jobs, retrieval jobs and repositioning jobs. While the origin of a storage job is usually a designated handover area, where containers are forwarded from horizontal-transport equipment to the storage machines, its destination is a position in a yard block that has been determined by solving the stacking problem. Vice versa, the origin of a retrieval job is located in a yard block and its destination is located in a handover area. For repositioning jobs, both origin and destination are located in a yard block.

In a mid-sized container terminal, hundreds of transport jobs have to be scheduled for the storage machines per operating hour. However, comparable to the vehicle-dispatching problem (see Sect. 2.4.3.5) only some transport jobs that occur in the next few minutes are usually classified as plannable, due to the underlying online character of this planning problem. In addition, the scheduling problem may be further reduced by regarding the transport jobs of each yard block as a distinct planning problem. The exact structure of the storage-machine-scheduling problem depends on the deployed type of storage equipment, due to determining where the handover between the storage and horizontal-transport machines takes place. In case SCs are used for the waterside horizontal transport, a handover to other storage machines may not even be necessary, as these are active horizontal-transport machines which can also stack the containers in the yard blocks by themselves (see Sects. 2.2.3.2 and 2.4.3.5).

In the fashion of the vehicle-dispatching problem, the superior objective of the storage-machine-scheduling problem is the minimisation of the vessel-berthing time. However, this objective cannot be directly applied and therefore several objectives are reported for this problem: maximising the equipment productivity, minimising empty-driving and waiting times of the equipment, minimising the makespan and synchronisation with the horizontal-transport system. An extensive overview on these scheduling objectives and a discussion on how they foster the superior terminal objectives is given in Sect. 3.2.

2.5 Concluding Remarks

Container terminals are very special from a material-handling point of view. For several reasons—mainly because of the particular attributes of containers and the applied handling equipment—they cannot be treated as large, open-air variants of classical warehouses (Meersmans and Dekker 2001). In this chapter, an introduction into the field of container logistics is given, in particular, the container terminal and the related planning problems are presented. OR can provide valuable contributions for the solution of these problems. Therefore, the number of OR publications has remarkably increased over the last two decades along with the growing economic importance of the container-logistics sector. Nowadays, several hundred OR papers on container-terminal-related planning problems are available, but still not all planning problems are treated satisfyingly. In addition, new handling equipment and improving information systems continuously lead to modified or even completely new planning problems for seaport container terminals.

By introducing the terminal functions, subsystems and planning problems, it is already indicated in this chapter that the storage yard is of utmost importance for the functionality and the performance of a seaport container terminal as a whole. In the next chapter, the storage yard of seaport container terminals is regarded in more detail—different storage-yard systems are compared and the related processes and performance figures are discussed. Thereby special attention is given to some of the latest developments within the field of storage equipment—namely automated RMGC systems—whose planning problems are not yet completely treated in the OR literature.

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