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Container terminal operation and operations research – a classification and literature review

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Abstract. In the last four decades the container as an essential part of a unit-load-concept has achieved undoubted importance in international sea freight transportation. With ever increasing containerization the number of seaport container terminals and competition among them have become quite remarkable. Operations are nowadays unthinkable without effective and efficient use of information technology as well as appropriate optimization (operations research) methods. In this paper we describe and classify the main logistics processes and operations in container terminals and present a survey of methods for their optimization.

Keywords: Container terminal – Logistics – Planning – Optimization – Heuristics – Simulation

1 Introduction/historical overview

Containers came into the market for international conveyance of sea freight almost five decades ago. They may be regarded as well accepted and they continue to achieve even more acceptance due to the fact that containers are the foundation for a unit-load-concept. Containers are relatively uniform boxes whose contents do not have to be unpacked at each point of transfer. They have been designed for easy and fast handling of freight. Besides the advantages for the discharge and loading process, the standardization of metal boxes provides many advantages for the customers, as there are protections against weather and pilferage, and improved and simplified scheduling and controlling, resulting in a profitable physical flow of cargo. Regarding operations, we need to distinguish whether we refer just to a container (which in that sense is called a box) or we specify the type of container

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under consideration. The most common distinction refers to a so-called standard container as one which is twenty feet (20’) long, describing the length of a short container. Other containers are measured by means of these containers, i.e., in twenty feet equivalent units (TEU) (e.g., 40’ and 45’ containers represent 2 TEU). Additional properties of containers may be specified whenever appropriate (e.g., the weight or weight class of a container, the necessity of special handling for reefer containers or oversized containers).

First regular sea container service began about 1961 with an international container service between the US East Coast and points in the Caribbean, Central and South America. The breakthrough after a slow start was achieved with large investments in specially designed ships, adapted seaport terminals with suitable equipment, and availability (purchase or leasing) of containers. A large number of container transshipments then led to economic efficiency and a rapidly growing market share. In this context, transshipment describes the transfer or change from one conveyance to another with a temporarily limited storage on the container yard.

Today over 60 % of the world’s deep-sea general cargo is transported in containers, whereas some routes, especially between economically strong and stable countries, are containerized up to 100 % [140, 78]. An international containerization market analysis shows that in 1995 9.2 million TEU were in circulation. The container fleet had almost doubled in ten years from a size of 4.9 million TEU in 1985. Figure 1 shows the container turnover for the ten largest seaport terminals in the world from 1993 to 2002 [16, 17, 3, 4, 148]. Due to the positive forecast for con-

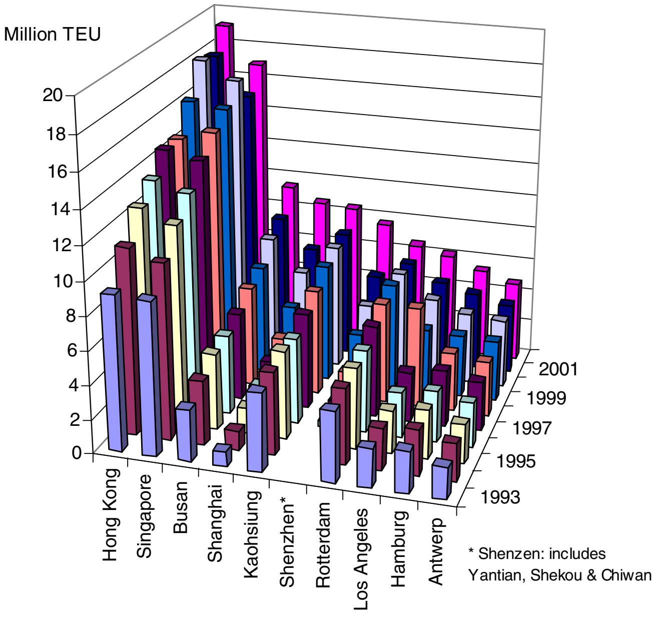

Fig. 1. Container turnover of the ten largest seaport terminals in the world from 1993 to 2002 (ranking 2002)

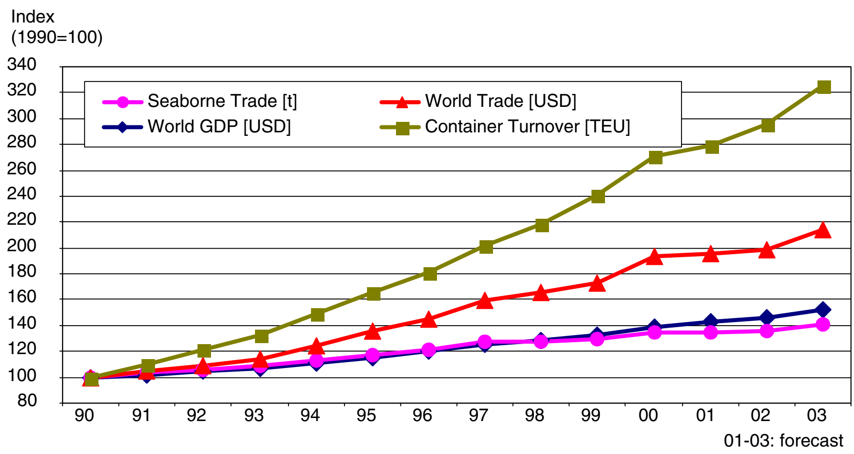

Fig. 2. Containerization trend: high growth of container turnover

tainer freight transportation, a similar development can be expected in the future. Figure 2 shows the containerization trend with high increasing rates compared with the rates of world trade, seaborne trade and the gross domestic product (GDP) of the world [198].[1]

The increasing number of container shipments causes higher demands on the seaport container terminals, container logistics, and management, as well as on technical equipment. An increased competition between seaports, especially between geographically close ones, is a result of this development. The seaports mainly compete for ocean carrier patronage and short sea operators (feeders) as well as for the land-based truck and railroad services. The competitiveness of a container seaport is marked by different success factors, particularly the time in port for ships (transshipment time) combined with low rates for loading and discharging [140, 78]. Therefore, a crucial competitive advantage is the rapid turnover of the containers, which corresponds to a reduction of the time in port of the container ships, and of the costs of the transshipment process itself. That is, as a rule of thumb one may refer to the minimization of the time a ship is at the berth as an overall objective with respect to terminal operations.

The objective of this paper is to provide an overview and a classification of container terminal operations. Moreover, based on this classification we attempt to provide a comprehensive literature review concerning operations research models and applications in this important logistics field. Usually, container terminals are characterized by means of their specific equipment and stacking facilities. Therefore, in Section 2.1 we describe possible means of handling equipment used in today's container terminals. Based on these one may classify various types of con-

[1] For detailed information about worldwide maritime transport trends see actual UNCTAD Review of Maritime Transport (via http://www.unctad.org), e. g. [189–192]. Success factors for growth in container shipping can be found in [198] or [118]. An introductory overview of intermodal freight transportation and containerization is given by [127, 140].

tainer terminals (see Section 2.2). Furthermore, we provide a general overview of the functionality of a container seaport terminal with a focus on physical container movements. In Section 3 we discuss terminal logistics and optimization methods. Here we aim at providing a considerable list of relevant references (in many cases just providing the references without going too much into detail) describing different approaches including exact methods, heuristic methods as well as simulation based approaches.[2] Finally some conclusions are given in Section 4.

2 Terminal structure and handling equipment

In general terms, container terminals can be described as open systems of material flow with two external interfaces. These interfaces are the quayside with loading and unloading of ships, and the landside where containers are loaded and unloaded on/off trucks and trains. Containers are stored in stacks thus facilitating the decoupling of quayside and landside operation.

After arrival at the port, a container vessel is assigned to a berth equipped with cranes to load and unload containers. Unloaded import containers are transported to yard positions near to the place where they will be transshipped next. Containers arriving by road or railway at the terminal are handled within the truck and train operation areas. They are picked up by the internal equipment and distributed to the respective stocks in the yard. Additional moves are performed if sheds and/or empty depots exist within a terminal; these moves encompass the transports between empty stock, packing center, and import and export container stocks (Fig. 3).

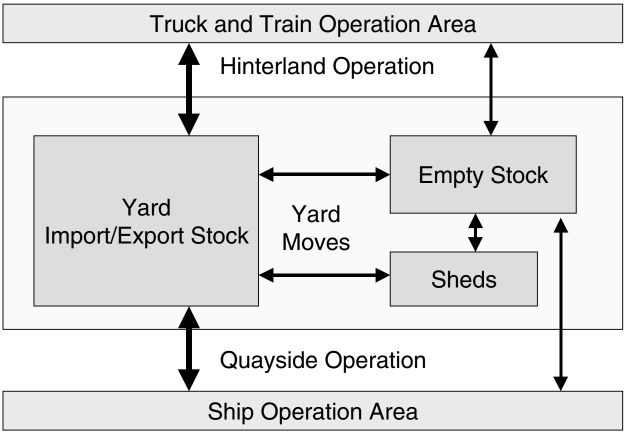

Fig. 3. Operation areas of a seaport container terminal and flow of transports

[2] All sections are moderately interleaved with references giving pointers to relevant literature. Although we try to achieve a more comprehensive list of references than other recent survey papers in this field (see, e.g., [196]) we admit that even our list is by no means complete.

It should be noted that the quayside operation or container transshipment as well as the container movement to and from the wharf is sometimes also referred to as waterside transshipment process. Correspondingly, one may find the terms hinterland transshipment processes and landside transshipment processes.

Different types of ships have to be served at the quayside. The most important ones are deep-sea vessels with a loading capacity of up to 8.000 container units (TEU) which serve the main ports of different countries and continents. Such vessels are about 320 m long with a breadth of 43 m and a draught of 13 m; on deck containers can be stowed 8 tiers high and 17 rows wide, in the hold 9 high and 15 wide. The ships' data call for respective dimensions of the cranes' height and jib length. Loading of about 2.000 boxes is common in large ports; the same is valid for unloading. Feeder vessels with a capacity of 100 to 1.200 TEU link smaller regional ports with the oversea ports delivering containers for deep-sea vessels. Inland barges are used to transport containers into the hinterland on rivers and channels. Functionally, barges are means of hinterland transportation (like trucks and trains), operationally they are ships which are served by quay cranes.

Trucks have a capacity of up to three TEU. At container terminals they are directed to transfer points where they are loaded and unloaded. To serve trains, railway stations with several tracks may be part of container terminals. The capacity of one train is about 120 TEU. Shuttle trains connecting a terminal with one specific hinterland destination obtain increased importance. The modal split of hinterland transportation is very specific for different ports which has a direct impact on the terminals' layout and type of equipment.[3]

The container storage area is usually separated into different stacks (or blocks) which are differentiated into rows, bays and tiers. Some stack areas are reserved for special containers like reefers which need electrical connection, dangerous goods, or overheight/overwidth containers which do not allow for normal stacking. Often stacks are separated into areas for export, import, special, and empty containers.

Besides in these general functions some terminals differ also in their operational units. For example, if railway stations do not exist inside the terminal, containers have to be transported by trucks or other landside transportation means between the external station and the terminal. This results in additional logistic demands.

Other differences occur if sheds exist within the terminal area. At sheds containers are stuffed and stripped, and goods are stored. Additional movements have to be performed connecting the yard stacks with the sheds. The same applies to empty depots where empty containers are stored according to the needs of shipping lines.

[3] The figures for Hamburg, Rotterdam, Hong Kong and Singapore illustrate this quite clearly (see, e.g., [184] for Rotterdam): Hamburg: about 47 % truck, 35 % feeder and 18 % rail; Rotterdam: about 50 % truck, 40 % feeder, 10 % rail; Hong Kong: more than 90 % truck, less than 10 % feeder, no rail; Singapore: 20 % truck, 80 % feeder, no rail.

2.1 Handling equipment

Usually, container terminals are described very specifically with respect to their equipment and stacking facilities. From a logistic point of view, however, terminals only consist of two components: stocks and transport vehicles.

The yard stacks, ships, trains, and trucks belong to the category 'stock'. Stocks are statically defined by their ability to store containers while from a dynamic point of view a stowage (or loading) instruction is necessary defining the rules how and where containers have to be stored. There is no principal difference between these different types of stocks but only a difference in capacity and complexity. Routing and scheduling of ships, trains and trucks do not belong to container terminal operation. Therefore, they can be considered statically as storage entities whereas a stowage instruction exists in any case even for trucks where at least the position of the containers to be loaded has to be defined. For specific stowage, ships and trains need instructions defining the position for every container. Transport means either transport containers in two or three dimensions. Cranes and vehicles for horizontal transport belong to this category. Their logistical specifics are that transport jobs have to be allocated to the means of transport and sequences of jobs have to be performed. The calculation of sequences is typical for the transportation means and defines a principal difference to the stocks categorized above. Not looking for these identities but being fixed on the specifics of each component and equipment applied at container terminals results in a variety of operations research approaches and solutions.

2.1.1 Types of cranes. Concerning cranes, different types are used at container terminals. The quay (or gantry) cranes (Fig. 4a) for loading and unloading ships play a major role. Two types of quay cranes can be distinguished: single-trolley cranes and dual-trolley cranes. The trolleys travel along the arm of a crane and are equipped with spreaders, which are specific devices to pick up containers. Modern spreaders allow to move two 20' containers simultaneously (twin-lift mode). Conventionally single-trolley cranes are engaged at container terminals. They move the containers from the ship to the shore either putting them on the quay or on a vehicle (and vice versa for the loading cycle). Single-trolley cranes are man-driven. Dual-trolley cranes represent a new development only applied at very few terminals. The main trolley moves the container from the ship to a platform while a second trolley picks up the container from the platform and moves it to the shore. The main trolley is man-driven while the second trolley is automatic. At modern cranes, the crane driver is supported by a semi-automatic steering system; this is both the case for one and two-trolley cranes.

The maximum performance of quay cranes depends on the crane type. The technical performance of cranes is in the range of 50–60 boxes/h, while in operation the performance is in the range of 22–30 boxes/h.

A second category of cranes is applied to stacks. There are three types of cranes, either rail mounted gantry cranes (RMG) or rubber tired gantries (RTG) and overhead bridge cranes (OBC). Rubber tired gantries are more flexible in operation while rail mounted gantries are more stable and overhead bridge cranes are mounted on

a b

Fig. 4a,b. Quay cranes and stacking crane. **a** Quay crane (here: dual-trolley cranes). **b** Stacking crane (here: Double-RMG)

concrete or steel pillars. Commonly gantry cranes span up 8–12 rows and allow for stacking containers 4–10 high. To avoid operational interruption in case of technical failures and to increase productivity and reliability, two RMGs are often employed at one stack area (block). Containers which have to be transported from one side of the block to the other then have to be buffered in a transition area of the block. Double-RMG systems represent a new development. They consist of two RMGs of different height and width able to pass each other thus avoiding a handshake area (Fig. 4b). This results in a slightly higher productivity of the system. Although most of the gantry cranes are man-driven, the tendency is for automatic driverless gantry cranes which are in use at some terminals (e.g. Thamesport, Rotterdam, Hamburg). The technical performance of gantry cranes is approximately 20 moves/h.

Similar cranes are used for loading and unloading trains. They span several rail tracks (about six). Containers to be transferred from/to trains are pre-stowed in a buffer area alongside the tracks.

Forklifts and reachstackers are used to move and stack light containers – especially empty ones.

2.1.2 Horizontal transport means. A variety of vehicles is employed for the horizontal transport both for the ship-to-shore transportation and the landside operation. The transport vehicles can be classified into two different types. Vehicles of the first class are ‘passive’ vehicles in a sense that they are not able to lift containers by themselves. Loading and unloading of these vehicles is done by cranes, either quay cranes or gantry cranes. Trucks with trailers, multi-trailers and automatic guided vehicles (AGV, Fig. 5a) belong to this class. AGVs are robotics able to drive on a road network which consists of electric wires or transponders in the ground to control the position of the AGVs. AGVs can either load one 40’/45’ container or two 20’ containers – in the latter case multiple load operation is possible. As AGV systems demand for high investment, they are only operated where labour costs are high; they are now in operation at ECT/Rotterdam and at the HHLA/Hamburg – in combination with automatic gantry cranes.

a **b**

Fig. 5a,b. Horizontal transport means: Automated guided vehicle and straddle carrier. **a** AGVs (in front of quay cranes). **b** Straddle carrier

Transport vehicles of the second class are able to lift containers by themselves. Straddle carriers (Fig. 5b), forklifts, and reachstackers belong to this class. Straddle carriers (SC) are the most important ones of it. Straddle carriers not only transport containers, but are also able to stack containers in the yard. Therefore, they can be regarded as 'cranes' not locally bound, with free access to containers independent of their position in the yard. The straddle carriers' spreader allows to transport either 20' or 40' containers; twin mode to transport/stack two 20' containers simultaneously is becoming available. Because of their properties, straddle carrier systems are very flexible and dynamic. Straddle carriers exist in numerous variants. Usually straddle carriers are man-driven and able to stack 3 or 4 containers high, i.e., they are able to move one container over 2 or 3 other containers, respectively.

During the last years progress was made to develop automatic straddle carriers. Recently, an automatic straddle carrier system has gone into production at Patrick Terminal/Brisbane, Australia. The straddle carriers are 4 high, an integrated system of differential GPS (see Section 2.1.3) and dead-reckoning serves for accurate positioning and routing. Beside this type of normal height, automatic straddle carriers of less height (height one or two) are under development. Because of the restricted height they are not provided for stacking but transport purposes only. Their ability for lifting containers allows for decoupling the work flow of transport and crane activities by using buffers at the respective interfaces. Because of the ability to lift containers, automated straddle carriers are often named Automated Lifting Vehicles (ALV).

2.1.3 Assisting systems. Besides cranes and transport vehicles, assisting systems play an eminent role for the organization and optimization of the work flow at container terminals. This is valid especially for communication and positioning systems.

Container terminal operators support a very intense communication with external parties like shipping lines, agents, forwarders, truck and rail companies, governmental authorities like customs, waterway police and others. The electronic communication is based on international standards (EDIFACT; Electronic Data Interchange For Administration, Commerce and Transport). Every change of container status is communicated between the respective parties. From the point of view of the terminal operator the most important messages are: the container loading and discharging lists which specify every container to be loaded or unloaded to/from a ship with specific data; the 'bayplan' which contains all containers of a ship with their precise data and position within the ship (it is communicated before arrival in the port); the 'stowage instruction' which describes the positions where export containers have to be located in a ship and which is the base for the stowage plan of the terminal; container pre-advices for delivery by train and truck, and the schedule and loading instruction for trains – only to name a few. Although only some of these messages – especially the stowage instruction for ships and trains – interfere directly with the operational activities of the terminal, they are very important because they serve for completeness and correctness of container data which is necessary to optimize the work flow.

Besides the communication with external partners, the internal communication systems play a major role in optimizing the terminal operation. The radio data communication, which was installed at container terminals since the middle of the 1980s, plays a key role because it is the main medium to transmit job data from the computer to cranes and transport vehicles. The radio data communication was the technical base for the implementation of operations research methods to optimize job sequences.

Since the middle of the 1990s Global Positioning Systems (GPS) were installed at container terminals. Initially they were used to automatically identify the position of the containers in the yard guaranteeing that the container yard position in the terminals' computer system is accurate. Because of the size of containers and the yard layout, differential GPS (DGPS) is necessary. DGPS components are not installed at containers but on top of the transport and stacking equipment. The position is measured, translated into yard coordinates and transmitted to the computer whenever a container is lifted or dropped. Alternatives to DGPS are optical based systems, especially Laser Radar. Sometimes both systems are integrated to assure a higher reliability. Container positioning systems like DGPS, dead-reckoning or Laser Radar constitute the technical base for the improvement of yard and stacking logistics.

Transponder and electrical circuits are used to route gantry cranes and automatic vehicles like AGVs whereas DGPS is used for the steering of automatic straddle carriers and other equipment.

Literature review

General information about technical equipment for container terminals can be found in engineering oriented journals as well as specialized outlets (see, e.g., http://www.porttechnology.org/). For different types of cranes and their use see, e.g., [147, 180]. Mobile vehicles or crane installations are also described in [127, 140, 147]. A more general insight into transport vehicles or gantry cranes is provided by, e.g., [127, 140, 106]. For a detailed overview of current state of the art handling technologies for terminal operations – like Automated Storage and Retrieval Systems (AS/RS) or AGVs – see, e.g., [85, 84, 83]. The use of DGPS at a container terminal is reported in [179]. Embedding handling equipment into more general aspects of innovation management at container terminals is considered in [199].

An interesting comparison between different types of container terminals based on specific types of equipment is provided in [168]. The authors compare the waterside productivity in different scenarios for manually operated SCs, AGVs and ALVs in a system set with yard stacking cranes. In addition they provide cost estimates based on simulation studies.

An overview of research on the potential of an integrated approach with usage of AS/RS and an AGV system is given in, e.g., [87, 5, 6]. Variations with different technical equipment – new in the field of container terminals – are shortly discussed. Effectiveness of such systems is compared with performance of current conventional systems by simulation experiments. For example, a 'Grid on Rail' concept is proposed: conventional container blocks are served by an overhead grid network of rails and a fleet of shuttle cranes moving on it. Effects are better space utilization by a more compact yard without necessity of roads between blocks and faster storage/retrieval operations than in conventional approaches with gantry cranes or straddle carriers. A pilot design is located in Hong Kong.

Details about assisting systems (without any planning functionality) can be found, e.g., on the web pages of service companies. This also includes detailed handbooks for electronic data interchange (EDI and EDIFACT) or hints for contractual agreements (see, e.g., http://www.dakosy.de and [79]).

2.2 Container terminal systems

A great variety of container terminals exists mainly depending on which type of handling equipment is combined to form a terminal system. All terminals use gantry cranes, either single- or dual-trolley, manual or semi-automatic. The transport between quay and stack can be performed either by trucks with trailers, multi-trailers, AGVs or straddle carriers. These vehicles can also serve the landside operation – except AGVs which nowadays are exclusively engaged at the quayside. Container stacking is either performed by gantry cranes or by straddle carriers.

Despite the variety of equipment combinations, two principal categories of terminals can be distinguished: pure straddle carrier systems and systems using gantry cranes for container storage.

Terminals with gantry cranes for container storage apply any kind of transport vehicles mentioned above. Even mixed systems of transport vehicles occur; e.g., multi-trailers for the quayside and straddle carriers for the landside operation. Up to now AGV terminals only exist in combination with automatic gantry cranes. Trains are normally loaded and unloaded by gantry cranes even in case of straddle carrier terminals, although in some cases straddle carriers are also used for this purpose (see Fig. 6).

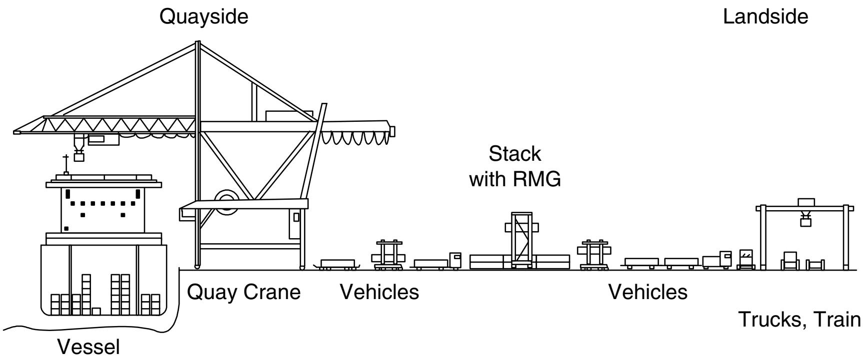

Fig. 6. Container terminal system (schematic side view, not true to size)

The decision on which equipment is used at container terminals depends on several factors. Space restrictions, economical and historical reasons play an important role. A basic factor is the dimension of the space which can be used for a terminal. If space is restricted, gantry cranes to store containers are preferred. A decision for AGVs and automated gantry cranes can be made in case of high labour costs and new terminal construction. Historical and cultural reasons have to be considered if container terminals are enhanced or modernized. Because space is becoming a scarce resource, a tendency for higher storage is to be foreseen.

Besides the mentioned two main categories, common in Europe and Asia, a third type, quite often in North America, is an on-chassis system, in which containers are stored on chassis instead of being stacked on top of each other. This system lacks of special stacking cranes, has simpler stacking logistics and is more space demanding. Its logistic aspects are covered by the other two systems.

Literature review

Container terminal operations are becoming more and more important. Therefore, an ever increasing number of publications on container terminals have appeared in the literature. While we refer to most of them in the subsequent chapters, some deserve special mention due to some of their general perspectives.

Decision problems at container terminals are comprehensively described by Vis and de Koster [196] (with some 55 references up to 2001). An overview of relevant literature for problem classes like arrival of the ship, (un)loading of a ship, transport of containers from/to ship to/from stack, stacking of containers, inter-terminal transport and complete terminals is provided.

Kozan [112] discusses major factors for the transfer efficiency of multimodal container terminals. A network model reflecting the logistic structure of a terminal and the progress of containers is shown. Its objective is the minimization of the total throughput time as the sum of handling and travelling times of containers. Earlier work of the same author is [111].

Meersmans and Dekker [132] present an overview of the use of operations research models and methods in the field of design and operation of container terminals with its decision problems on strategic, tactical and operational level.

Fung [50] presents a three-player oligopoly error-correction model for forecasting demand for Hong Kong's container handling services. Due to increasing demand and necessity of higher throughput, early construction of new terminals is suggested.

Murty et al. [141] describe various interrelated complex decision problems occurring daily during operations at a container terminal. They work on decision support tools and discuss mathematical models and algorithms.

Steenken [180] presents a comprehensive description of logistics and optimization systems in container terminals – shown by example of 'Burchardkai' (Hamburg).

For an early work on berth assignment and berth investment decisions see [45]. A general discussion of different productivity related objectives regarding transshipment terminals can be found, e.g., in [49,62]. Additional works giving more or less general descriptions of container terminals are, e.g., [34,130]. In [34] the authors view a container terminal as a production system that is represented as a network of complex substructures or platforms. The idea of platform capacity is used to represent operational aspects of a container terminal in a mathematical model for tactical planning. The problem is to allocate resources in each platform in order to minimize the total delay on the overall network and time horizon.

Konings [108] presents a survey of the possibilities for an intermodal transport concept of high quality. Conditions for best development of centers, that integrate transshipment, storage, collection and distribution of goods, are outlined. The internal transport system is identified as key element. The topic is discussed in detail for the harbour of Rotterdam.

Nam and Ha [142] investigate aspects of adoption of advanced technologies such as intelligent planning systems, operation systems and automated handling systems for container terminals. They set criteria for evaluation of different handling systems and apply them to examples in Korea. Results show that automation does not always guarantee outperformance (e.g. higher productivity) – it depends on terminal characteristics such as labour costs.

Four different types of automated container terminals are designed, analyzed and evaluated in a simulation model with very detailed cost considerations by Liu et al. [126]. The performance criteria that are used in this study to evaluate and compare different terminal systems are summarized as follows: Throughput: number of moves/hour/quay crane; throughput per acre; ship turnaround time: time it takes for a ship to get loaded/unloaded; truck turnaround time: average time it takes for a truck to enter the gate, get served, and exit the gate, minus the actual processing time at the gate; gate utilization: percent of time the gate is serving the incoming and outgoing container traffic; container dwell time: average time a container spends in the container terminal before taken away from the terminal; idle rate of equipment: percent of time the equipment is idle. The authors conclude that performance and costs of conventional terminals can be improved substantially by automation.

Important features of a terminal are related to the location of equipment and resources over the terminal. This refers, e.g., to resource allocation problems but also to some dispatching problems. Objectives may be an intelligent assignment of technical equipment (e.g., gantry cranes and straddle carriers) to the different terminal areas as well as an efficient job assignment to the utilized resources (see, e.g., [113,54,181,32,155], or [177] presenting a method for forecasting daily demand in terms of the number of container movements in a terminal based on online data in order to improve supply side decisions like allocation of handling equipment, work scheduling, etc.). Moreover, in AGV systems the layout of the network for the vehicles (in manufacturing systems it is called guidepath network) has a major impact on system effectiveness. While optimization methods for guidepath network design have been considered for various production environments (see, e.g., [162, 105]), it may also become a thread in the layout of container terminals.

While most work is related to a single terminal, some harbours even have more than one terminal. Cheu et al. [28] discuss possible savings with respect to distances travelled for the harbour of Singapore under the assumption that different terminals are combined together into one so-called mega-terminal.

It should be noted that different types of 'terminals' may have the same or only slightly modified structure compared to container terminals. This may be easily seen from carefully investigating intermodal traffic terminals or so-called megahub terminals for rail traffic or even airports. As an example the reader may be referred to intermodal traffic terminals (see, e.g., [1,2,63]).

Many of the problems in container terminal logistics can be closely related to some general classes of transportation and network routing problems (and therefore more or less standard combinatorial optimization problems) discussed comprehensively in the literature. Examples of these problems and some basic references may be given as follows: An early and very comprehensive survey on various types of routing problems is [14]. For a recent survey on the vehicle routing problem (VRP) see [187], arc routing problems are also considered in [36]. The traveling salesman problem (TSP) asks for the shortest closed path or tour through a set of cities that visits every city exactly once. It is well explained in [116]; more recent pointers can be found in [65]. The rural postman problem (RPP), which is the problem of finding a least cost closed path in a graph that includes, at least once, each edge in a specified set of arcs, is considered, e.g., in [10]. For an application in container terminal logistics see [181]. In the pickup and delivery problem a set of routes has to be constructed in order to satisfy a given number of transportation requests by a fleet of vehicles. Each vehicle has a certain capacity, an origin and a destination (depot). Each transportation request specifies the size of the load to be transported, the location where it is to be picked up and the location where it is to be delivered.

The pickup and delivery problem is considered, e.g., in [35,64]. Finally, we mention the assignment problem, which is considered in almost any basic textbook on operations research.

3 Terminal logistics and optimization methods

The need for optimization using methods of operations research in container terminal operation has become more and more important in recent years. This is because the logistics especially of large container terminals has already reached a degree of complexity that further improvements require scientific methods. The impact of concurrent methods of logistics and optimization can no longer be judged by operations experts alone. Objective methods are necessary to support decisions. Different logistic concepts, decision rules and optimization algorithms have to be compared by simulation before they are implemented into real systems.

The characteristics of container terminal operation demands online (real-time) optimization and decision. This is because most of the processes occurring at container terminals cannot be foreseen for a longer time span – in general the planning horizon for optimization is very short. Some examples shall illustrate it: although data of containers to be delivered to terminals by trucks may be pre-advised by EDI, the exact time when the containers arrive at the terminal is not known.[4] On arrival, containers have to be checked for damages, and pre-advised data may be wrong; both data influence the target stack location. As trucks have to travel to transition points where the containers are picked up by straddle carriers or cranes, the truck sequences at the gate and at the transition points need not be the same. Thus only those container jobs can be sequenced which are already released for transportation by internal terminal equipment – in general only a few. As trucks permanently arrive, recalculation has to be performed periodically or event driven. Analogous arguments hold for train operation.

A similar situation occurs for ship loading and unloading. Although in general data of containers and their positions within the ship are precisely known in advance and the preplanning process (see below) allows the calculation of job sequences, they often have to be changed because of operational disturbances. As vessels are not static and move permanently (because of tide, weather, stability), containers which are next in the sequence cannot be accessed by the crane's spreader. Crane drivers make their own decisions and may alter the pre-calculated loading or unloading sequence by themselves.

According to the classification mentioned above, the following sections describe the most important processes at container terminals that can be optimized by means of operations research methods.

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[4] This is true for the north-west European ports, while East-Asian ports commonly prescribe a time-window of only several minutes when a truck has to enter a terminal.

3.1 The ship planning process

Ship planning consists of three partial processes: the berth planning, the stowage planning and the crane split.

3.1.1 Berth allocation. Before arrival of a ship, a berth has to be allocated to the ship. The schedules of large oversea vessels are known about one year in advance. They are transferred from the shipping lines to the terminal operator by means of EDI. Berth allocation ideally begins before the arrival of the first containers dedicated to this ship – on average two to three weeks before the ship's arrival. Besides technical data of ships and quay cranes – not all quay cranes can be operated at all ships – other criteria like the ship's length and the length of the crane jib have to be considered. All ships to be moored during the respective time period have to be reflected in berth allocation systems. Several objectives of optimized berth allocation exist. From a practical point of view the total sum of shore to yard distances for all containers to be loaded and unloaded should be minimized. This corresponds to maximum productivity of ship operation. Automatic and optimized berth allocation is especially important in case of ship delays because then a new berthing place has to be allocated to the ship whereas containers are already stacked in the yard.

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Berth planning problems may be formulated as different combinatorial optimization problems depending on the specific objectives and restrictions that have to be observed. As an example we mention the possibility to model berth planning by means of the resource constrained project scheduling problem. Restrictions may refer to special equipment that is needed for certain operations, as it is the case, e.g., for unavailability due to maintenance or for RoRo-ships[5] where tractor trailers need to drive into the ship. Connections of berth planning to assignment problems and especially to the quadratic semi-assignment problem are emphasized in [75]. Due to the large interdependency, berth and yard planning are frequently considered in a common optimization model [54, 19, 183].

Li et al. [120] discuss the more general problem of 'scheduling with multiple-job-on-one-processor pattern' with the goal of minimizing the makespan of the schedule. Vessels can represent jobs, a processor can be interpreted as a berth. Computational experiments show the effectiveness of a heuristic method with near-optimal results.

Lim [122] reformulates the problem as a restricted form of the two-dimensional packing problem and explores a graph theoretical representation. For this reformulation it is shown that this specific berth planning problem is NP-complete. An effective heuristic algorithm for solving the problem – applied to historical test data – is proposed.

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[5] A RoRo-ship is a Roll-On Roll-Off ship, i.e., transport vehicles can enter the ship via a stern ramp.

Legato and Mazza [117] present a queuing network model and a simulation experiment of the logistic processes (arrival, berthing and departure of vessels) at a container terminal.

Nishimura et al. [146] focus on the problem of dynamic berth assignment to ships in the public berth system (not especially container ports; it is emphasized that these systems and, therefore, the shown results 'may not be suitable for most container ports of major countries'). A heuristic procedure, based on a genetic algorithm (GA), is developed – 'adaptable to real world applications'.

Similar to [146], Imai et al. [81] study berth allocation and optimization of berth utilization using a heuristic procedure, which is based on a mixed-integer programming (MIP) formulation of static and dynamic versions of the allocation problem and its Lagrangian relaxation. The same authors develop a GA-based heuristic procedure for solving the nonlinear problem of berth allocation for vessels with different service priorities [82]. Imai et al. [80] relate berth allocation to machine scheduling problems and discuss a bi-objective nonlinear optimization problem considering ship waiting times and terminal utilization.

Based on [136], Kim and Moon [98] formulate a MIP-model for determining berthing times and positions of vessels in container ports with straight-line shaped berths. They develop a simulated annealing (SA) algorithm and show near-optimal results.

Guan and Cheung [60] propose a tree-search procedure and composite heuristics for large size problems in order to minimize total weighted flow time. Efficiency of the methods is shown by computational experiments.

Park and Kim [154] combine a berth assignment approach with consideration of quay crane capacities.

Additional references dealing with berth planning are, e.g., [115, 61, 153].

3.1.2 Stowage planning. Stowage planning is the core of ship planning. Planning a ship's stowage is a two-step process. The first step is executed by the shipping line. The shipping line's stowage plan has to be designed for all ports of a vessel's rotation. The positions for all containers and all ports of a rotation have to be selected within the ship. Stowage planning of a shipping line usually does not act with specific containers identified by numbers, but on categories of containers. These categories or attributes are: the length or type of a container, the discharge port and the weight or weight-class of containers. Containers of these attributes are assigned to specific positions within the ship. The objective of optimization from the shipping line's point of view is to minimize the number of shifts during port operation (ship to ship or ship to shore shifts) and to maximize the ship's utilization. Constraints to be satisfied mainly result from the stability of the ship.

The stowage plan of the shipping line is transferred to the terminal operator by EDI. The stowage instruction of the shipping line is filed into the terminal's system and serves as a working instruction or pre-plan for the terminal's ship planner. The stowage instruction of the shipping line is characterized by the assignment of containers of special attribute sets to ship slots. Based on this instruction the terminal planner then assigns dedicated containers identified by numbers to the respective slots. The attribute set of the slot and the container selected in the yard have to match. The stowage planning systems of a container terminal, therefore, display both the ship's sections to be planned and the yard situation. Some of the systems allow for automatic assignment and optimization. Different objectives of optimization are possible, e.g., maximization of crane productivity, cost minimization, or minimization of yard reshuffles. From a practical point of view the minimization of yard reshuffles plays an important role. Reshuffles occur when a container has to be accessed while others on top of it have to be removed first. Reshuffling consumes time which is an offset to the transportation time between stack and shore reducing the productivity of ship operation. Because the stowage plan is generated before the ship's loading has started, this kind of optimization is offline optimization.

Although stowage planning in real terminal operation is either a manual or an offline optimization process, the process structure of ship loading applies for online optimization. This is because the loading process and the stack-to-shore transport are more complex than yet described. To achieve a high productivity for the crane operation containers have to arrive at the quay in the right time and in the order of the loading sequence; i.e., loading sequence and sequence of horizontal transport have to correspond with each other. Otherwise crane waiting times and/or queuing of transport vehicles occur. Both reduce crane productivity and extend the ship's berthing time. As a common feature, containers are more or less spread in the yard and have different distances to the crane; special containers like overheight containers need special equipment which has to be mounted before they can be transported, reefer containers have to be disconnected from the electrical circuit, and yard reshuffles occur to a respective percentage. All this consumes additional transportation time. In manually driven systems the performance additionally depends on the driver's skill and decision which path he travels. Even technical or operational disturbances of the crane operation occur which enforce to change the loading sequence. Therefore, transportation times cannot be calculated exactly even if automated equipment is in use. All reasons together mean that the stowage plan prepared in advance can be sub-optimal. Online stowage planning is a solution to omit or at least reduce these problems. In online stowage planning a stowage plan which assigns specific containers to ship positions is no longer prepared. Instead containers are selected for transportation according to the attributes assigned to ship positions in the stowage instruction of the shipping line. Containers with the same attributes are considered as equal. They are then loaded according to their arrival time at the quay crane. Thus the specific stowage plan addressing specific container data to specific ship positions is generated simultaneously to the loading activity. Online stowage planning is not yet in use at container terminals but is a future need to enhance the performance of ship loading.

Literature review

In practice, stowage planning usually is a manual or offline optimization process using respective decision support systems (see, e.g., [176]). Most of the papers below describe research work applicable to enhance existing systems by appropriate optimization functionality. Container data are assumed to be given, i.e., we do not consider the problem of loading containers (see, e.g., [26,33,171,47]).

Sculli and Hui [173] investigate distribution effects and the number of different types of containers with respect to an efficient stowage in an experimental study. Performance of stacking policies is measured by volumetric utilization, wasteful handling ratios, shortage ratio, and rejection ratio. Results indicate that the number of different types of containers has the largest impact on these measures. Effects of stacking policy and maximum store dimensions are also significant.

Avriel et al. [9, 8] focus on stowage planning in order to minimize the number of unproductive shifts (temporary unloading and reloading of containers at a port before their destination ports in order to access containers below them for unloading). Aspects of ship's stability and other real-life constraints are not considered. A binary linear programming (LP) model is formulated. Due to the proven NP-hardness of the problem a so-called 'Suspensory Heuristic' – based on earlier work by Avriel and Penn [7] – is developed in order to solve even large problem instances. The heuristic assigns slots in a bay to containers dynamically with respect to the sequence of ports in a vessel's route.

Wilson and Roach [201, 202] divide the container stowage process into the two subprocesses and related subproblems of strategic and tactical planning level due to complexity of a stowage plan across a number of ports. They use branch and bound algorithms for solving the first problem of assigning generalized containers to a block in a vessel. In the second step a detailed plan which assigns specific positions or locations in a block to specific containers can be found by a tabu search algorithm. Good results (not always optimal) can be found in reasonable time. The same principles are described by Wilson et al. [203, 167]. They present a computer system for generating solutions for the decomposed stowage (pre-)planning problem illustrated in a case study. The authors present a GA approach in order to generate strategic stowage plans automatically. Initial computational experiments show effective sub-optimal solutions.

Haghani and Kaisar [66] propose a MIP model for developing loading plans in order to minimize the time that a vessel spends at port, and the container handling cost which is highly influenced by the number of unproductive but necessary shifts caused by an unsatisfactory arrangement of containers. Loading schedules, ship's parameters like strength and stability, and factors like longitudinal moment, trim, and metacentric height are taken into consideration. Solution procedures and computational test examples are proposed.

Dubrovsky et al. [37] use a GA for solving the stowage planning problem of minimizing the number of container movements. Search space is significantly reduced by a compact and efficient encoding scheme. Ship stability criteria are reflected by appropriate constraints. Simulation runs demonstrate the efficiency and flexibility of the GA-based approach.

Simulation and online optimization in stowage planning is considered in [205, 204, 182]. Especially in online settings as they are encountered in practice, waiting times of the cranes as well as congestions of transport means below the cranes have to be minimized to avoid productivity reduction. Winter [204] presents an integrated just-in-time scheduling model and algorithms for combined stowage and transport planning. In the first step a crane split is computed, based on the shipping company's stowage plan and a resulting loading sequence of bay positions and container types, respectively. The overall loading process is then optimized by flexibly assigning containers to straddle carriers fulfilling stowage criteria and minimizing late arrivals at the quay cranes. The assignment is based on container attributes instead of container numbers. Precedence constraints and transportation times depending on different travel distances (yard – quay) are considered, too. The model and the algorithms are tested with real-world data showing suitability for real-time planning with its special difficulties like delays of containers or incomplete information. A shorter version is given in [182].

Giemsch and Jellinghaus [57] present a MIP model for the stowage problem, based mainly on [9, 8] and [202]. The basic model is extended with additional constraints and solution methods are modified. Results show improvements in comparison with [9].

For further references on stowage planning see, e.g., [86].

3.1.3 Crane split. The third step of ship planning is the allocation of quay cranes to ships and the ships' sections – the crane split (scheduling). Depending on the ship's size commonly three to five cranes operate at one oversea vessel. Feeder ships are operated with one to two cranes. In practice, crane to ship allocation has to reflect several constraints – especially technical data of cranes and ships and the accessibility of cranes at a berth. Because terminals are historically grown, in general different types of cranes exist at real terminals. The number of cranes operable at one berth in general is restricted because not every crane can be driven to every berth.

Crane split allocates a respective number of cranes to a ship and its sections (bays) on hold and deck and decides on which schedule the bays have to be operated. It not only reflects one ship but several ships – in neighboured berths and principally all ships moored at a terminal in a given period. There is no unique objective for optimization. Minimization of the sum of the delays of all ships can be an objective while maximization of one ship's performance or a well-balanced or economic utilization of the cranes can be others. In real terminal practice it depends on the actual terminal situation and the terminal's goal. In addition to the crane split, crane allocation decides on the mode how a ship and the ship's bays are loaded. A bay can be loaded either horizontally or vertically, starting at the quay or at the waterside, resulting in four different modes of loading. There are additional modes but these are the main ones. Stowage plan, crane split, and mode of loading together result in a working instruction which defines the loading sequence for every container of a bay. As mentioned earlier, the sequence for the landside transport has to match this loading sequence.

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Daganzo [32] shows a MIP for a static crane allocation problem with no additional ships arriving during the planning horizon. It is exactly solved for small problem instances (i.e. small number of ships), and a heuristic procedure for larger problems is proposed. In addition, the dynamic problem is considered. In both models the berth length is assumed to be unlimited.

Peterkofsky and Daganzo [155] study a branch and bound method for minimizing delay costs. Exact solutions for problems described in [32] are given in order to speed up the time-intensive and, therefore, cost-intensive (un)loading process.

Gambardella et al. [52] present a solution for the hierarchical problems of resource allocation – namely the allocation of quay cranes for (un)loading vessels and yard cranes for stack operations – and scheduling of equipment (i.e. (un)loading lists for each crane). Simulation results show reduction of equipment conflicts and of waiting times for truck queues. (See also related earlier papers of members of the same group of authors: [54, 129, 210, 166, 165, 53].)

The crane split as part of an integrated stowage and transport planning problem is discussed in [204,182] as mentioned in Section 3.1.2.

Bish [12] develops a heuristic method for minimizing the maximum turnaround time of a set of ships in the so called 'multiple-crane-constrained vehicle scheduling and location problem (MVSL)'. The problem is threefold: determination of a storage location in the yard for unloaded containers, dispatching vehicles to containers and scheduling of (un)loading operations to cranes.

Park and Kim [154] discuss an integer programming model for scheduling berth and quay cranes and propose a two-phase solution procedure. A first near-optimal solution for finding a berth place and time for each vessel and assigning the number of cranes is refined by a detailed schedule for each quay crane.

3.2 Storage and stacking logistics

Stacking logistics has become a field of increasing importance because more and more containers have to be stored in ports as container traffic grows continuously and space is becoming a scarce resource. Generally containers are stacked on the ground in several levels or tiers and the whole storage area is separated into blocks. A container's position in the storage area (or yard) is then addressed by the block, the bay, the row and the tier. The maximum number of tiers depends on the stacking equipment, either straddle carriers or gantry cranes. According to operational needs the storage area is commonly separated into different areas. There are different areas for import and export containers, special areas for reefer, dangerous goods or damaged containers. The average daily yard utilization of large container terminals in Europe is about 15.000–20.000 containers resulting in about 15.000 movements per day. The dwell time of containers in the yard is in the range of 3–5 days at an average.

A storage planning or stacking decision system has to decide which block and slot has to be selected for a container to be stored. Because containers are piled up, not every one is in direct access to the stacking equipment. Containers that are placed on top of the required one have to be removed first. Reshuffles (or rehandles) may occur due to several reasons; the most important ones result if data of containers to be stacked are wrong or incomplete. At European terminals 30–40 % of the export containers arrive at the terminal lacking accurate data for the respective vessel, the discharge port, or container weight – data which are necessary to make a good storage decision. Even after arrival, vessel and discharge port can be changed by the shipping line. For import containers unloaded from ships the situation is even worse: the landside transport mode is known in at most 10–15 % of all cases at the time of unloading a ship, e.g., when a location has to be selected in the yard.

To ease the situation and to ensure a high performance of ship, train and truck operation, containers sometimes are pre-stowed near to the loading place and in such an order that it fits the loading sequence. This is done after the stowage plan is finished and before ship loading starts. Because pre-stowage needs extra transportation, it is cost extensive and terminals normally try to avoid it by optimizing the yard stacking, but it is executed when ship loading has to be as fast as possible. Storage and stacking logistics are becoming more complex and sophisticated; they play an important role for the terminals' overall performance.

Two classes of storage logistics can be distinguished. In storage or yard planning systems, stack areas and storage capacities are allocated to a ship's arrival in advance according to the number of import and export containers expected. An appropriate number of slots in blocks and rows are reserved for a special ship. Depending on the planning strategy, the reservation for export containers can be split for discharge port, container type/length, and container weight. A common strategy for export planning is to reserve slots within a row for containers of the same type and discharge port while heavier containers are stacked on lighter ones assuming that they are loaded first because of the ship stability. For import containers only a reservation of yard capacity of respective size is done without further differentiation. This is because data and transport means of delivery generally are unknown at the time of discharge. If the transport mode is known, import areas can be subdivided according to them. Common strategies for import containers are either selecting any location in the import area or piling containers of the same storage date.

Yard or storage planning seldom matches the real delivery because container delivery is a stochastic process not exactly to be foreseen. The quality of this yard concept mainly depends on the strategy how to determine a good stack configuration and a good forecast of the container delivery distribution. Both factors are hard to solve, the result is a comparatively high amount of yard reshuffles. In addition, the reservation of yard locations occupies stack capacity.

Because of these disadvantages some terminals installed an alternative stacking concept, called scattered stacking. In scattered stacking, yard areas are no longer assigned to a specific ship's arrival but only once to a berthing place. On arrival of a container the computer system selects the berthing place of the ship from the ships schedule and automatically searches for a good stack location within the area assigned to the berth. A stack position is selected in real-time and containers with the same categories – ship, type/length, discharge port, and weight – are piled up one on top of the other. Containers for one ship are stochastically scattered over the respective stack area; reservation of yard slots is no longer necessary. This concept results in a higher yard utilization – because no slots are reserved – and a remarkable lower amount of reshuffles – because the stacking criteria merge the ship's stowage criteria.

Although the container attributes play a major role in yard stacking concepts, additional parameters have to be taken into account for improving logistic processes. Evidently, containers have to be stacked near to the future loading place, e.g., the transport distance should be minimal to ensure a high performance of the future operation. The performance of quay cranes is a multitude higher than the performance of stacking and transport equipment. Therefore, containers with the same categories have to be distributed over several blocks and rows to avoid congestions and unnecessary waiting times of vehicles. The actual workload of a gantry crane or other stacking equipment also has to be considered because allocating additional jobs to highly utilized equipment provokes waiting times. All these factors can be integrated into an algorithm while the weight of each factor is measured by parameters. The objective of yard optimization is to minimize the number of reshuffles and to maximize the storage utilization.

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Cao and Uebe [22] propose a tabu search based algorithm for solving the transportation problem with nonlinear side constraints – a general form of the problem of assignment of storage positions for containers with minimized searching and/or loading costs and satisfaction of limited space and other constraints.

Kim [89] investigates various stack configurations and their influence on expected number of rehandles in a scenario of loading import containers onto outside trucks with a single transfer crane. For easy estimation regression equations are proposed.

Kim and Bae [90] propose a methodology to convert a current order of export containers in the yard into a bay layout which is best from the point of view of operations for loading a vessel. The goal is to find the fewest possible number of containers and/or shortest possible travel distance in order to minimize the total turn-around time of a vessel in a port. The problem is decomposed, mathematical models (dynamic programming, transportation problem) for the three subproblems are suggested, and a numerical example is given. The authors demand heuristic algorithms due to time consuming computations.

Kim and Kim [92–94] discuss the determination of optimal amount of storage space and optimal number of transfer cranes for import containers. The decision is based on a cost model including fixed investment costs and variable operation costs. A simple solution procedure and sensitivity analysis is illustrated with a numerical example. Two different objectives are considered: minimization of the costs of only the terminal operator and minimization of these costs combined with the costs of the customers. Deterministic and stochastic models and simple solution methods are provided and illustrated using numerical examples. In [93] the authors focus on strategies for storage space allocation. Cases with constant, cyclic and dynamic arrival rates of import containers are analyzed. The objective is minimization of the expected total number of rehandles. Mathematical models and solution procedures are shown and illustrated by numerical examples.

Kim et al. [100] formulate a dynamic programming model for determination of the storage location of export containers in order to minimize the number of reshuffles expected for loading movements. The configuration of the container stack, the weight distribution of containers in the yard, and the weight of an arriving container are considered. For real-time decisions a fast decision tree is derived from the set of optimal solutions provided by dynamic programming.

A GA-based approach for minimizing the turnaround time of container vessels is described by Preston and Kozan [157]. The problem is formulated as an NP-hard MIP-model for determining the optimal storage strategy for various schedules of container handling (random, first-come-first-served, last-come-first-served). Computational experiments show that the type of schedule has no effect on transfer time if a good storage layout is used. Changes of storage area utilization in the range of 10–50 % result in linear changes of transfer time.

Kim and Park [99] focus on export containers and show a dynamic space allocation method in order to utilize storage space efficiently and to increase efficiency of loading operations. A basic MIP-model is formulated. Two heuristic algorithms – a myopic (least-duration-of-stay) rule and a sub-gradient optimization technique – are compared in computational experiments. Results are in 'almost the same level of objective values', but the decision rule is much faster. Effects of changing values of several model parameters are also analyzed.

Zhang et al. [211] study the storage space allocation problem in a complex terminal yard (with inbound, outbound and transit containers mixed). In each planning period of a rolling-horizon approach the problem is decomposed into two levels and mathematical models. The workload among blocks is balanced at the first level. The total number of containers associated with each vessel and allocated to each block is a result of the second step which minimizes the total distance to transport containers between blocks and vessels. Numerical experiments show significant reduction of workload imbalances and, therefore, possible bottlenecks.

As mentioned in Section 2, empty containers are often stored separately from loaded containers due to the possibility of using different equipment to store them higher than loaded containers. While methods for storage and stacking of empty containers do not differ from the above described approaches, the distribution of empty containers to ports has been considered as a separate problem deserving specialized approaches (see, e.g., [31,175,29]).

Additional references for storage and stacking logistics are, e.g., [183,21,24, 27,76,95,113].

3.3 Transport optimization

Two types of transport at a container terminal can be distinguished: the horizontal transport and the stacking transport carried out by gantry cranes. The horizontal transport itself subdivides into the quayside and the landside transport serving ships or trucks and trains, respectively. Trucks, multi-trailers, AGVs, manned or automatic straddle carriers can be used for the transport.

3.3.1 The quayside transport. For ship loading and unloading containers have to be transported from stack to ship and vice versa. Transport optimization at the quayside not only means to reduce transport times but also to synchronize the transports with the loading and unloading activity of the quay cranes. A general aim is to enhance crane productivity. Crane productivity does not only depend on the technical data of the cranes (50–60 boxes/h). The real performance at operation is much lower (in the range of 22–30 boxes/h). The reduction is caused by unproductive times like pauses and breaks during shifts, moves of hatch covers and lashing equipment, technical or operational disturbances and congestions occurring for the horizontal transport. Additionally, more transport vehicles provoke further costs and ship operation then is less economic.

Concerning logistics, a gain in ship productivity cannot be necessarily achieved by enhancing the number or the speed of transport vehicles operating at the quayside. This is because the possibility of congestions at the cranes and in the yard increases more than proportionally with the number of vehicles or their speed. Therefore, developing an optimization system also has to cope with the minimization of congestions.

Different modes of transport and strategies to allocate vehicles to cranes occur at the quayside. In single-cycle mode the vehicles serve only one crane. According to the crane's cycle they either transport discharged containers from the quay to the yard or export containers from the yard to the crane. In dual-cycle mode the transport vehicles serve several cranes which are in the loading or unloading cycle, respectively, thus combining the transports of export and import containers. Transport vehicles can either be allocated exclusively to one crane (gang structure) or to several cranes and ships (pooling).

In single-cycle mode no potential for the optimization of the import cycle exists. Optimization for discharged containers is restricted to the selection of optimal yard positions which is a task of the yard planning module (see above). As import containers have to be transported to the pre-selected stack locations, empty travels cannot be reduced. Travel distances can only be reduced if locations near to the quay are selected.

For export loading, however, there is a potential for optimization. In general the transport sequence is not identical to the loading sequence of the ship. The loading sequence is determined by the stowage plan, the crane split and the crane's loading strategy. The transport sequence, however, has to reflect different distances, yard reshuffles and special containers. The latter ones sometimes need special equipment which has to be provided before they can be transported. All effects result in additional transportation times. Therefore, the transport sequence has to be altered to ensure the right order of the loading sequence. Idle times of the cranes and vehicle congestions at cranes and stacks have to be avoided because both reduce productivity.

The dual-cycle is more complex. The dual-cycle mode combines the transports of export and import containers to/from cranes operating at the same ship or at neighbouring ships. The fixed allocation of transport vehicles to cranes is given up, vehicles operate in a pool serving several cranes in alternative modes (loading or discharging). Empty distances and transportation times are reduced in dual-cycle mode. This mode is more efficient but harder to organize because of the higher complexity. The possibility of crane waiting times can be reduced if containers can be buffered under the crane's portal.

In terminal practice, automatic transport vehicles like AGVs are always pooled while manned equipment like straddle carriers or trucks commonly operate at one crane (fixed allocation). If the loading capacity exceeds one container a multiple load mode is possible. Multiple load for AGVs contains potential for optimization, but it rarely occurs in practice because it is hard to organize. If unmanned equipment like AGVs or ALVs for transportation and automated gantry cranes for stacking are used, a main task of the control system is to synchronize the equipment in a way that the containers arrive 'in-time' at the interfaces (of the equipment such as, e.g., cranes and AGVs) and the idle times (of the cranes) are minimized.

Ship operation in practice is dynamic and, therefore, demands online optimization. For import containers, e.g., the precise yard location cannot be selected before the container is unloaded and its data and condition is physically checked. Disturbances occurring during ship operation often force to alter the loading or unloading sequence immediately. Such disturbances are: interruption of crane operation because of operational or technical problems, change of (un)loading sequences decided by the crane driver because of ship stability reasons or problems occurring during the horizontal transport. Such reasons force (re)calculating sequences only for few containers. The objective of optimization in any case is to minimize the lateness of container deliveries for the cranes and the travel times of the transport vehicles.

Literature review

A literature review regarding quayside transport is almost a dime a dozen and may be distinguished mainly based on the means of transport, i.e., AGVs, straddle carriers, etc. Even within the first category (AGVs) the number of references is enormous as AGVs are commonly used in warehouse operations and flexible manufacturing systems (see, e.g., [162] for a survey). In the sequel we first provide a wealth of references regarding AGVs before we are considering other means of transport.

Evers and Koppers [48] focus on movements of AGVs over the physical infrastructure with their model of an AGV traffic control system and the so-called semaphore technique.

Bruno et al. [18] focus on the control problem of dynamic determination of waiting positions for idle AGVs in order to reach good overall performance of the system (the paper deals with general material handling systems). Two fast effective heuristic algorithms are discussed and tested in real-world scenarios. The shown approach (without taking into account any information about future events) has better results than the traditional point-of-release-positioning rule.

Gademann and van de Velde [51] determine the waiting locations for idle AGVs in a loop layout with uni- or bidirectional flow system. The problem is restricted to a static setting, in which all AGVs are assumed to be idle at the same time. Objective functions are functions of travel times from the nearest waiting location of an AGV to a pickup point.

Wallace [200] presents an agent based AGV controller in order to provide effective flow even in complex designs. Agents allow AGVs to allocate only small possible segments or points on their paths. The agent approaches are tested in computational experiments with two layouts and are compared with an 'AutoMod' simulation. Results show higher efficiency without any deadlock situation.

Van der Heijden et al. [72] develop rules for management of empty AGVs in (general) automated transportation systems. Their performance (in terms of service levels, AGV requirements and empty travel distances) is evaluated by simulation. Look-ahead rules outperform the simple first-come-first-served rule.

Leong [119] develops an efficient dynamic deployment algorithm scheme for AGVs, that dispatches AGVs to containers in order to minimize the (un)loading time for a vessel. A deadlock prediction and avoidance algorithm – developed in [137] and also discussed later in [138] – is integrated. The new scheme is compared with the current scheme (used at a terminal in Singapore) in a simulation experiment. Analysis of results shows improvements, since the throughput is increased by the new scheme.

In a similar paper concerning the same project as in [119], Chan [25] models a network flow in order to develop an efficient dispatching strategy for AGVs. Constraints describe disparate instances of AGVs carrying one container or two containers. The performance of the proposed heuristic algorithms is tested and – in case of single load – compared with the current deployment strategy, that is outperformed by the new one.

Reveliotis [164] proposes a robust conflict resolution strategy for flexible operations on arbitrarily structured path networks. A dynamic closed-loop control scheme is developed, which organizes dispatching and routing of AGVs on basis of real-time feedback on the system traffic. Although the paper does not focus on automated container terminals, results may be transferred to this field.

Qiu and Hsu [158–161] address scheduling and routing problems for AGVs. They develop conflict-free routing algorithms for two different path topologies and two scheduling strategies. The methods are applied together in a case study.

Qiu et al. [162] provide a survey of scheduling and routing algorithms for AGVs. They show similarities and differences between scheduling and routing of AGVs and related problems like the vehicle routing problem, the shortest path problem, scheduling problems or others. They classify algorithms in groups for general path topology (static/time-window based/dynamic methods), for path optimization (0-1-integer-programming model, intersection graph method, integer LP model), for specific path topologies (linear/loop/mesh topology) and dedicated scheduling algorithms.

Grunow et al. [58, 59] focus on dispatching multi-load AGVs. A flexible priority rule based approach is proposed and compared to an alternative MIP formulation in different scenarios. Reduction of AGVs' lateness in case of multi-load mode is shown and an improvement of the terminal's overall performance is expected. In addition, a MIP is developed that allows determining optimal solutions for small problem instances. For real applications a hybrid approach using the MIP combined with fast heuristics on some special dispatching requests is suggested. A different MIP formulation can be found in [172].

Hanafi et al. [67] extend the simple multi-load case to the following problem related to container terminal logistics. Given a pool of containers, the container assignment problem consists of determining on which barges containers have to be loaded to minimize the total number of barges used while satisfying a number of side constraints. Different models and methods are compared on data provided by the Port of Lille.

Hartmann [68] develops a general scheduling model consisting of assignment of jobs to resources and (temporal) arrangement of the jobs with consideration of constraints. This model can be applied for scheduling of AGVs, straddle carriers, gantry cranes and even workers. A heuristic method based on priority rules and a GA for solving the problem are discussed and compared in a computational experiment, that shows promising results for the GA.

Yang et al. [207] analyze an increase of terminal productivity due to using ALVs rather than AGVs – based on the observation of unproductive and costly waiting of AGVs under quay cranes and in the blocks compared to that of ALVs. By means of a simulation model it is demonstrated, 'that the ALV is superior to the AGV in both productivity and economical efficiency principally because the ALV eliminates the waiting time in the buffer zone'. Similar findings are reported by [195].

Lim et al. [123] do not especially focus on container terminals, but suggest an auction algorithm as dispatching method for AGVs in a general context. The method implements a distributed decision process with communication among related vehicles and machines for matching multiple tasks with multiple vehicles. Future events are taken into account as well. Outperformance is shown by a simulation study.

Ulusoy et al. [188] address the problem of simultaneous scheduling of machines and a number of identical AGVs in a flexible manufacturing system in order to minimize the makespan. The discussed ideas and the GA may be transferred to problems arising at container terminals, especially the simultaneous scheduling of RMGs and AGVs.

Routing of straddle carriers for loading export containers is discussed by Kim and Kim [96]. The objective is the minimization of total travel distance of straddle carriers in the yard. The routing problem is composed of the container allocation problem – formulated as a transportation problem – and a carrier routing problem with given sequence of yard-bays to be visited by a carrier. The routing problem is solved by a beam search algorithm, that is evaluated in numerical tests. In [103] the number of containers picked up by a straddle carrier at each bay and the sequence of bay visits are determined in order to minimize total travel distance/time of the carrier. The proposed integer programming model is solved by a two-phase procedure. Sequencing of individual containers is not studied.

Böse et al. [15] investigate different dispatching strategies for straddle carriers to gantry cranes in order to reduce vessel's turnaround time at port by maximizing productivity of gantry cranes achieved by an efficient schedule of given straddle carriers. The potential of evolutionary algorithms for solving the considered allocation problem is shown in computational experiments based on real data (without taking stochastic influence into account). Different vehicle assignment strategies are suggested. The first approach suspends the static binding of carriers to gantry cranes using a dynamic strategy where a predetermined number of carriers perform container transports for several gantry cranes (straddle carrier pooling). Depending on the number of loading and discharging processes (structure of the waterside transshipment process), the carriers can be used in a double-cycle mode such that empty runnings are replaced by jobs for other gantry cranes. Two different cases of straddle carrier pooling are considered: semi-dynamic assignment (a fixed number of straddle carriers is assigned to the gantry cranes of one vessel) and dynamic assignment (a fixed number of straddle carriers can perform transports for all gantry cranes). Considering an online optimization setting, numerical results for real data may show that the influence of the number of sequenced containers need not have a large influence when the carriers operate in double cycle mode [128].

Li and Vairaktarakis [121] address the problem of minimizing the (un)loading time for a vessel at a container terminal with fixed number of internal trucks (not shared among different vessels). An optimal algorithm and some heuristic algorithms are developed for the case of a single quay crane. Effectiveness of the heuristics is shown by analysis and computational experiments. The case with multiple identical quay cranes is not solved, but the complexity is analyzed.

Bish et al. [13] focus on the NP-hard vehicle-scheduling-location problem of assigning a yard location to each import container and dispatching vehicles to the containers in order to minimize the total time for unloading a vessel. A heuristic algorithm based on an assignment problem formulation is presented. The algorithm's performance is tested in computational experiments.

Meersmans and Wagelmans [134] consider the problem of integrated scheduling of AGVs, quay cranes and RMGs at automated terminals. They present a branch and bound algorithm and a heuristic beam search algorithm in order to minimize the makespan of the schedule. Near optimal solutions are obtained in a reasonable time. In [133] a beam search algorithm and several dispatching rules are compared in a computational study under different scenarios with similar results. The study also indicates 'that it is more important to base a planning on a long horizon with inaccurate data, than to update the planning often in order to take newly available information into account'. These results are also included in the PhD-thesis of Meersmans [131].

Carrascosa et al. [23] present a multi-agent system architecture to solve the automatic allocation problem in container terminals in order to minimize the ships' docking time. The paper focuses on the management of gantry cranes by a 'transtainer agent'. This work is framed into a project to the integral management of the containers terminal of an actual port. The independence of subsystems obtained from a multi-agent approach is emphasized. (The approach is also described by the same group of authors in [163].)

Kim et al. [91] discuss the load sequencing problem for export containers in terminals with transfer cranes and yard trucks. They introduce various objectives and constraints. A flexible beam search algorithm for minimizing total handling time of cranes and trucks is suggested. Comparison of performance with other approaches shows high quality of the proposed algorithm.

3.3.2 The landside transport. The landside transport is split into the rail operation, the truck operation and the internal transports. A common means of operation is to allocate a given number of vehicles to each sphere of operation appropriate to the workload expected. A more advanced strategy is to pool the vehicles for all these working areas.

Trains are commonly loaded and unloaded by gantry cranes while the transports between the stack and the railhead are performed by straddle carriers, trucks and trailers or similar equipment. Containers are then buffered alongside the railhead or directly on trailers. Sometimes pure straddle carrier operation exists where straddle carriers drive over the wagons to pick up and drop containers.

Operation at the railhead is analogous to the quayside operation. A loading plan describes on which wagon a container has to be placed. The wagon position of a container depends on its destination, type and weight, the maximum load of the wagon and the wagon's position in the train sequence. A loading plan is either produced by the railway company and sent by EDI to the terminal operator or by the terminal operator himself. The aim of the rail operator is to minimize shunting activities during train transport while the aim of the terminal operator is to minimize the number of yard reshuffles, to minimize the crane waiting times and the empty transport distances of cranes and transport vehicles. Optimization at the railhead is facilitated if only a stowage instruction is sent to the terminal operator which indicates the wagon position for container attributes instead of specific positions for each container. The yard situation then can be reflected. Transport and crane activities have to be synchronized to avoid unnecessary crane waiting times or movements. Single- and dual-cycle mode exist depending on whether one or several trains are loaded and unloaded in parallel.

Trucks arrive at the terminal's in-gate where the data of the containers have to be checked and filed into the computer system or actualized in case of pre-advice. Trucks then drive to transition points where the containers are loaded or unloaded by internal equipment. Large container terminals serve some thousand trucks a day. Transition points are located either at the stack crane or inside the yard in case of straddle carrier operation. A truck driving schedule prescribes which points have to be accessed in which sequence. The arrival time of the trucks at the transition points cannot be precisely foreseen, i.e., transport jobs for the internal equipment cannot be released until the truck arrives at the transition point. Because of the permanently changing traffic volume, optimization has to be very flexible and fast. Online optimization is demanded for. Minimizing empty distances and travel times are the objectives of optimization at the truck operation area. Empty distances can be minimized if transports of export containers from the transition point to the yard are combined with transports of import containers from the yard to the interchange point.

Internal movements occur because of different reasons. If sheds or depots for empty containers exist at a terminal additional transports have to be performed: Import containers to be stripped have to be driven to the respective shed while packed containers have to be driven to the export stock. Empty containers are needed at the sheds for stuffing purposes while unpacked containers have to be stored in the empty depot or in the yard. Because of imbalances, empty containers are needed for ship, train and truck loading and have to be transported to the respective yard or transition area. Additional transports occur when containers assigned for a ship's departure are left back because of ship's overbooking. A reorganization of the yard then has to be performed. Characteristic for these types of transports is that sequences of jobs have to be performed. Sometimes time-windows have to be kept.

In general these kinds of transports are not as time critical as those for the ship or truck operation. Therefore, terminals try to execute them at times of less workload. The objective is to minimize empty and loaded travel times.

Literature review

Powell and Carvalho [156] propose a dynamic model for real-time optimization of the flow of flatcars considering constraints for assignment of trailers and containers to a flatcar. A smaller flatcar fleet is possible due to useful information for decision makers provided by the developed global logistics queueing network model.

Steenken [178] investigates methods to optimize the straddle carrier operation at the truck working area. The problem of assigning jobs to straddle carriers is solved with linear assignment procedures combining movements for export und import containers. Steenken et al. [181] deal with the optimization for the rail operation and internal moves. Different algorithmic approaches are used to solve the routing problems, as they can be found in machine scheduling, for solving the travelling salesman problem, the rural postman problem, etc. Both solutions were implemented in a real time environment and resulted in considerable gains of productivity. Results and architecture of implementation are presented in [180].

Kim et al. [97] discuss approaches and decision rules for sequencing pickup and delivery operations for yard cranes and outside trucks, respectively. Their goal is to maximize the service level of trucks by minimizing the turnaround time of them, both for automated and conventional terminals. A dynamic programming model for a static case (all arrivals of trucks are known in advance) is suggested. For a dynamic case (new trucks arrive continuously) a learning-based method for deriving decision rules is proposed besides several heuristic rules. The performances of the methods are compared in a simulation study. The rule of serving the truck with the shortest transfer time (sum of travel time and time for transferring the corresponding container to and from the truck, including occurring rehandling time) shows good, robust performance in various situations, whereas the learned rules outperformed other methods in case of non-uniform distribution of containers' arrival locations. The authors conclude that their single crane based approaches can be extended to the multiple crane case.

Koo et al. [109] present a two-phase fleet sizing and vehicle routing procedure for container ports with several yards. The goal is to find the smallest required fleet size and a route for each vehicle to fulfill all transportation requirements within a static planning horizon. A computational study shows solutions of good quality in comparison with two other existing methods.

3.3.3 Crane transport optimization. Another field of application of optimization methods are the transports of gantry cranes operating in stacks. The transport requirements do not differ from those of the horizontal transport described above. Sequences of jobs have to be calculated and jobs have to be assigned to the respective crane. Commonly the location of a container to be positioned in the stack is calculated by the yard module. This is also true for the containers which have to be reshuffled. Therefore, transport optimization for stack cranes reduces to the same requirements as for the horizontal transport and comparative algorithms can be applied. Priority of jobs have to be taken into account – as is the case for the horizontal transport. The objective of optimization is to minimize the waiting times of the transport vehicles at the stack interfaces and the travel times of the stacking cranes. Because the traffic at the interfaces changes rapidly online optimization is demanded for and job sequences have to be recalculated whenever a new job arises.

Literature review

Due to interdependencies of crane operations and quayside, landside and stack operations, references regarding crane transport optimization may be reviewed in either section as we have done above; see, e.g., [155, 92–94, 12, 97].

Kim and Kim [102] present a routing algorithm for a single gantry crane loading export containers out of the stack onto waiting vehicles. The objective is to minimize the crane's total transfer time including set-up and travel times. The model's solution determines the sequence of bay visits for pick-up operations and the number of containers to be picked up at each bay simultaneously. The developed algorithm is named 'efficient' and shows solutions to problems of practical size 'within seconds'. In a more detailed paper [95] the same algorithm is used for solving the MIP of a 'practical problem of a moderate size'. The load sequence of individual containers within a specific bay remains undetermined.

Kim and Kim [104] extend their problem shown in [102] and [95] to general yard-side equipment, such as gantry cranes or straddle carriers. Experiments show that the proposed beam search algorithm outperforms a GA. The pick-up sequence for individual containers in a bay remains undetermined as in [95].

Lin [124] deals with the problem of scheduling movements of RTGs among different storage blocks in order to balance the workload and minimize the total unfinished workload at the end of each time period. The complexity of the MIP is analyzed. Besides the Lagrangian decomposition solution procedure, a new approach ('successive piecewise-linear approximation') is discussed. This solution method can be applied to large size problem instances since computational experiments show efficiency and effectiveness. The same results are published later by Cheung et al. [30].

Narasimhan and Palekar [144] consider the minimization of a yard gantry crane's handling time for executing a given load plan with a given bay plan for export containers. An exact branch-and-bound based algorithm and a heuristic method are developed and tested by computational experiments on randomly generated problem instances. Besides the algorithmic approaches the authors provide a mathematical programming formulation and also consider some complexity issues.

Zhang et al. [212] describe the dynamic RTG deployment problem with forecasted workload per block per planning period (4 hours). The objective is to find times and routes of RTG movements among blocks with minimization of total delayed workload in the yard. For safety reasons a maximum of two RTGs per block is allowed. Only one transfer of a RTG in and out of a block can occur. The problem is formulated as a MIP model and is solved by a modified Lagrangian relaxation with excellent results.

A similar group of authors [125] solve this RTG deployment problem in a different way. The size of the problem is reduced by sorting blocks into categories like ‘sink block’ (needs and can take additional help), ‘source block’ (can spend capacity of RTGs) and ‘neither block’ (needs help but cannot take help, because two RTGs currently work in the block, or it does not need help). Neither blocks are excluded in the model. A pre-sort step identifies eligible RTGs and sink blocks, a following deployment step (formulated as MIP model) results in the optimal RTGs’ deployment plan for source and sink blocks. The approach is tested with a set of real operation data (Hong Kong). Results demonstrate ‘an excellent capability and potential of the model in minimizing the crane workload overflow’.

Routing and/or scheduling algorithms for multiple cranes are hardly addressed in literature. A simulation study on operational rules for Double-RMGs is shortly discussed by Kim et al. [101]. Crane dispatching rules with and without different roles for the different cranes and sequencing roles are tested. A second simulation study focuses on determining the storage location of arriving containers.

In [46] we consider the case of Double-RMGs and develop possible solution approaches for specific sequencing and scheduling problems in order to take advantage of using two cranes – which can overtake each other – instead of one crane and increase the terminal’s throughput.

3.4 Simulation systems

In recent years, simulation has become an important tool to improve terminal operation and performance. Three types of simulation can be distinguished: strategical, operational and tactical simulation.

Strategical simulation is applied to study and compare different types of terminal layout and handling equipment in respect to efficiency and costs expected. It is mainly used if new terminals are planned or the layout or the equipment of existing terminals has to be altered. Strategical simulation systems allow for easy design of different terminal layouts and employment of different types of handling equipment. The chief goal of strategical simulation is to decide on terminal layout and handling equipment which promises high performance and low costs. To match reality, simulation systems allow to design realistic scenarios or to import data of existing terminals.

Operational simulation is applied to test different kinds of terminal logistics and optimization methods. It has achieved growing acceptance at least at large terminals. Terminal operation and logistics at large terminals are already very complex and the effect of alternative logistics or optimization methods has to be tested with objective methods. Therefore, optimization methods are tested in a simulation environment before they are implemented in real terminal control and steering systems.

Tactical simulation means integration of simulation systems into the terminal’s operation system. Variants of operation shall be simulated parallel to the operation and advices for handling alternatives shall be given especially if disturbances occur in real operation. Real data of operation then have to be imported and analyzed synchronously to the operation. Because of this ambitious requirement, tactical simulation is seldom or only partially installed at container terminals.

Literature review

Simulation results provide valuable decision support information for terminal planners, operators, and managers (see, e.g., [56, 70, 107, 139, 77, 186, 135, 145, 185, 169, 170]). Therefore, various groups have worked in simulation systems for container terminals; see, e.g., [54, 129, 166] or work based on [15].

A group of authors [42, 114, 150, 149, 38, 151, 193, 41, 39, 44, 40, 43, 152, 194] demonstrate the usage of simulation for development of an automated container terminal by example of Rotterdam. The performance of (sub)systems with AGVs, ALVs, multi-trailers/manned trucks is tested. Valuable insights can be obtained about optimal stack height, optimal number of AGVs and other variables.

Bruzzone et al. [20] demonstrate effectiveness of simulation for supporting complex container port management. Presented application examples and experimental results show benefits in reusability, flexibility, modelling time, and performance estimation of a simulation approach.

Gehlsen and Page [55] present a framework (written in Java) for simulation projects including heuristic optimization procedures (GA) in a parallel distributed environment.

Liu et al. [126] use future demand scenarios to design the characteristics of different terminals in terms of configuration, equipment and operations. A microscopic simulation model is developed and used to investigate each terminal system for the same operational scenario and evaluate its performance. Moreover, a cost model is developed evaluating the cost associated with each terminal concept. Results indicate that automation could improve the performance of conventional terminals substantially at a considerably lower cost.

Nam et al. [143] examine optimal number of berths and quay cranes for a terminal in Busan (Korea). Different operational patterns are represented in four scenarios for performance evaluation by simulation experiments. Results reveal that ‘sharing quay cranes with adjacent berths can increase productivity, and that the more berths per operator, the higher the productivity achieved’. Terminal development and operation policy implications are considered. Topics for further studies are given.

Shabayek and Yeung [174] describe a simulation model to simulate the Kwai Chung container terminals in Hong Kong. They investigate accuracy of prediction of actual terminal operations and conclude with good results.

Kia et al. [88] describe the role of simulation for evaluating the performance of a terminal’s equipment and capacity. Performance criteria and interesting model parameters are discussed.

Hartmann [69] develops an approach for generating realistic scenario data of port container terminals as input for simulation models and for test of optimization algorithms. A scenario consists of data concerning arrivals of ships, trains and trucks within a time horizon and information about containers being delivered or picked up. Users can control various typical parameters.

Yun and Choi [208, 209] propose an object-oriented simulation model for analysis of container terminals consisting of gate, container yard, berth and equipment like transfer cranes, gantry cranes, trailers, and yard tractors. Output of resource statistics can be used for analysis of capacity and operational efficiency of an existing container terminal.

Saanen et al. [169, 168] use simulation models to account for cost values of different types of equipment to be installed at a terminal. Examples are based on the layout of terminals in Hamburg and Rotterdam where using straddle carriers versus AGVs or ALVs is compared with respect to productivity values. One of the major results is that at a certain point adding further equipment can no longer increase productivity (or even lead to decreasing productivity, e.g., if too many vehicles are blocking each other). Similar results are presented by Steenken [180].

Vis and Harika [195] study the performance of AGVs and ALVs. A simulation experiment shows effects on unloading times of a vessel using different equipment. A sensitivity analysis is performed. Results show that the optimal type of equipment and fleet size depend on the terminal's design and technical aspects of quay cranes. Investigations regarding the number of AGVs can also be found in [197].

Analytical approaches that use modern queuing techniques instead of discrete-event simulation in order to evaluate terminal allocation and layout planning problems can be found in, e.g., [110, 71].

4 Conclusions and outlook

The increasing number of publications in the last decade indicates the importance of operations research methods in the field of optimizing logistic operations at a container terminal. Until now the focus is not on optimizing the transport chain as a whole but on optimizing several separate parts of the chain. A tendency from relatively theoretical publications to more practical ones can be seen. Furthermore, operations research methods are applied more and more in real terminals. One of the drivers in this respect is an increased availability of modern information and communication technology that only allows the application of these methods.

High operating costs for ships and container terminals and also high capitalization of ships, containers and port equipment demand a reduction of unproductive times at port. Therefore, the potential for cost savings is high. A key to efficiency is the automation of in-yard transportation, storing and stacking to increase the terminal throughput and decrease ship turnaround time at the terminal. Due to severe competition the increasing pressure on container terminals to cut costs of operation and to increase productivity enforces the usage of optimization methods.

At terminals which already apply operations research methods to optimize transport and stacking processes, the need for 'integrated' optimization is becoming more and more relevant. The transport process between quay and yard or between hinterland and yard is broken into separate phases because different types of equipment are engaged for the whole transport chain. Additionally, containers have to be buffered in respective handshaking areas. In practice, optimization commonly is restricted to the partial phases of the whole transport or to rules (heuristics) for the handshaking. Thus not all sources of optimization are exploited, but high performing operations ask for it. An example shall be given which explains the problem: A solution for the crane split can allow that two (or more) cranes operate very close together at a ship. This can be optimal for the crane operation, but it will not be for the horizontal transport because then the cranes are not easily accessible by the vehicles and congestions are provoked. An integrated optimization of both the crane split and the horizontal transport is demanded for. Similar problems can be found for every transport or stowage process at container terminals.

Up to now there are only a few studies on such 'integrated problems' – e.g., in [134] or in [74, 73], presenting a multi-agent system approach with several agents (agents for ship, berth, yard, and gate and utility agents for quay crane, gantry crane and transport) – although they are important for enhanced terminal performance. Therefore, 'integrated optimization' should be a field of increased investigation.

Besides the major research needs regarding the topics online optimization as well as integration, additional topics may become important. Operations research approaches for container terminals usually apply simulation when it comes to consideration of stochasticity. However, the area of stochastic optimization and scenario based planning may be applied, too. For instance, vehicle routing problems with time windows and stochastic travel times or with stochastic customers (see, e.g., [206, 11]) may be important areas worth considering for container terminal operations.

Finally, a new challenge is given by advanced security issues. They will imply more versatile planning tools for optimization. Usage of techniques like, e.g., transponders and certain security procedures and their impact on the logistic chain have to be taken into account.

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