Vehicle Routing Problems and Container Terminal Operations – An Update of Research

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Summary. Containers came into the market for international conveyance of sea freight almost five decades ago. The breakthrough was achieved with large investments in specially designed ships, adapted seaport terminals with suitable equipment, and availability of containers. Today over 60 % of the world's deep-sea general cargo is transported in containers and some routes are even containerized up to 100 %. Seaport container terminals face a high demand for advanced optimization methods. A crucial competitive advantage is the rapid turnover of the containers, which corresponds to an efficient handling of containers as well as to a decrease of the costs of the transshipment processes. One of the key concerns in this respect refers to various types of equipment at container terminals devoted to the routing of containers to achieve high productivity. For instance, a variety of vehicles is used for the horizontal transport at the quayside and at the landside.

In this chapter we provide a comprehensive survey on routing problems that have arisen in the container terminal domain, such as how to route automated guided vehicles, new technologies such as double rail mounted gantry cranes, etc. This opens up new challenges for the field. The chapter strives to summarize the research results for the vehicle routing problem and its variants regarding container terminals.

Key words: Vehicle routing problem; container terminal operations; scheduling; automated guided vehicles; straddle carriers; rail mounted gantry cranes; quay cranes; trucks; trailers.

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1 Introduction

Containerization – the stowage of regularly or even irregularly shaped freight in sealed, reusable boxes with standardized dimensions – is one of the most important cargo-moving techniques developed in the 20th century. Being highly efficient, it has influenced and revolutionized not only the shipping industry and ports, it has also fundamentally changed the whole international trade as well as concept, design, functions and activities of transport systems in the world. Intermodality with transformed ship-to-shore links, ship-to-rail links and ship-to-ship transhipment links have been developed and refined. Containers can be used worldwide in several transportation systems. They can be loaded on large seagoing vessels (and in small number on aircrafts) – typically for inter-continental transport – and on feeders, trains and trucks for intra-continental transport. Even high-value cargo can be transported quickly in a cost-efficient way. Today over 60 % of the world's deep-sea general cargo is transported in containers and some routes are even containerized up to 100 % [65, 106]. For detailed information about worldwide maritime transport trends see current *UNCTAD Reviews of Maritime Transport* (via http://www.unctad.org), e. g. [141]. Success factors for growth in container shipping can be found, e.g., in [72, 94, 150].

The number and capacity of seaport container terminals has increased and will increase in the future. However, in the short term increased cargo amounts have to be handled at today's container terminals with given limited capacity. This fact still encourages port authorities and container terminal operators to redesign the buffering and handling of containers to more efficiency, rather to keep up with higher cargo amounts than to decrease costs [8, 130, 147].

The demurrage of a container ship causes a high rate of the total costs in the shipping process. The potential of cost savings is high. High operating costs for ships and container terminals as well as high capitalization of ships, containers and port equipment demand the reduction of unproductive times at port. The superordinate goal is to reduce the time for the discharging and loading process of a ship [136]. Speed is very important in the global transport of goods, not only for the carrier but also for a terminal, since the competition among container terminals has increased.

Recent developments have shown that a key to efficiency (in container handling) is the automation of in-yard transportation, storing and stacking to increase the terminal throughput and decrease ship turnaround time at the terminal [10]. High productivity can be achieved with various types of equipment, e.g., vehicles used for horizontal transport of containers at the quayside and at the landside. *Passive vehicles* like trucks with trailers or automated guided vehicles (AGVs) are employed in combination with cranes. Being a mixture of a yard trailer and a transfer crane, *active vehicles* such as straddle carriers (SCs) have free access to containers independent of their position in the yard. Common SCs are manned, but during the last years automated lifting vehicles (ALV) were developed. The ongoing trend focuses on improvements of terminal configurations, i.e. the use of automated container handling and transportation equipment. Therefore, particularly in countries with high labor costs, manually operated vehicles are going to be replaced by automated ones. These strategic decisions focusing on terminal layout, multi-modal interfaces, equipment selection, berthing capacity and information systems are the basis for operational planning as well as the real-time control of, e.g., crane scheduling and operation sequencing [53]. Routing and scheduling are most essential parts of tactical and operational planning.

The goal of this chapter is to provide an expository update of research on the vehicle routing problem (VRP) and its variants and modifications regarding container terminal operations. In this respect we extend and update the paper of Steenken et al. [136]. While [136] provides a comprehensive survey of the state-of-the-art of operations at a container terminal as well as methods for their optimization, in this chapter we restrict ourselves towards routing. Although some older references are provided for the sake of keeping the context we focus on work being published in recent years, especially since 2004. Since we focus on operations at terminals, ship routing problems or a liner operator's problem of distributing or reusing empty containers, i.e. finding best (multimodal) container itineraries, are excluded as well as vehicle routing with pick up and delivery of full container load from/to an intermodal terminal and similar problems (see, e.g., [19, 22, 29, 66, 76, 77, 95, 96, 108, 132]).

This chapter is organized as follows. First we provide some background regarding the problem domains to understand the settings in which the VRP and its variants arise. Therefore, the next two sections describe briefly some general concerns of vehicle routing and the structure of seaport container terminals with their different operation areas. Different combinations of handling equipment result in different terminal systems with different problems regarding vehicle routing and scheduling. After this condensed view and classification of terminal systems, Section 4 as the main body of our chapter provides deeper insight into the most important typical processes at a terminal with focus on routing problems of the employed vehicles like AGVs, SCs and transfer cranes. Brief literature reviews are presented. The chapter is concluded with a summary and outlook identifying interesting or promising topics for future research.

2 Routing and Scheduling

General classes of vehicle routing and transportation problems are discussed comprehensively in the literature. Since many problems in container terminal logistics can be closely related to these classes, some basic references may be helpful for container terminal oriented research. It should be noted that although these standard problems associated with dispatching/routing vehicles, assigning equipment to jobs or locating items arise frequently in logistic systems and, therefore, are extensively studied, most of this research seems not directly applicable at container terminals. The terminals' unique characteristics, some of which are described in the next section, must be taken into account in modeling and developing algorithms.

Bodin et al. [11] present an early and very comprehensive survey on various types of routing problems. Toth and Vigo [140] and Cordeau et al. [28] provide surveys on the VRP, arc routing problems are also considered by Dror [34]. The traveling salesman problem (TSP) asks for the shortest closed path through a set of cities that visits every city exactly once. It is well explained by Lawler et al. [89]. More recent pointers can be found in [54]. The rural postman problem (RPP) 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. It is considered, e.g., in [6]. Steenken et al. [135] present an application of the RPP in container terminal logistics. In the pickup and delivery problem (PDP) 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 PDP is considered, e.g., in [32].

Finally, we mention the assignment problem, which is considered in almost any basic textbook on operations research. In a generalized context, e.g., ship routing can be defined as assignment of sequences of ports to be visited by ships. Scheduling brings temporal aspects into routing. Here, ship scheduling includes the timing of various events on a ship's route. For an overview regarding status and perspectives of ship routing and scheduling the reader is referred to, e.g., [23–25, 30, 38, 52, 64, 131].

Increasing complexity of logistics at container terminals demands for using optimization methods and scientific research in order to improve the handling operations. Objective methods are necessary for decision support. Different logistic concepts, decision rules and optimization algorithms have to be compared by simulation before they are implemented into real systems.

Most processes at container terminals cannot be foreseen for a longer time span. Overall, the planning horizon for optimization is very short. The characteristics of container terminal operation require online (real-time) optimization and decision. For example, the exact time when the containers arrive at the terminal is not known in all cases although data of containers may be pre-advised by electronic data interchange. Furthermore, pre-advised data may be wrong or containers could be damaged. Both data influence the target stack location. Some additional examples illustrate the complexity and very short planning horizon: Truck sequences at the gate can be different from the sequences at the transition points where the containers are picked up by SCs or cranes. 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. In general data of containers and their positions within the ship are precisely known in advance, and the preplanning process allows the calculation of job sequences. But the sequences 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 operation sequence.

Furthermore, conflict-free routing of AGVs is supported by fast algorithms that avoid collisions, deadlocks and livelocks at the time of route calculation.

3 Structure and Handling Equipment at Container Terminals

Seaport container terminals principally consist of the same sub-systems, although their size, function, transportation and handling equipment as well as layout considerably differ. In general terms, a container terminal can be described as an open system of material flow with two external interfaces: the quayside with loading and unloading of ships, and the landside where containers are loaded and unloaded on/off trucks and trains. The quayside and landside operations are decoupled by stacks for storing containers.

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 are expected to be transshipped next. Export containers arrive by trucks on road or by railway at the terminal. They are handled within dedicated 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 (Figure 1).

3.1 Handling Equipment

While container terminals can be described very specifically with respect to their equipment and stacking facilities, from a logistic point of view, terminals only consist of two components: static stocks and dynamic transport vehicles. Stocks are defined by their ability to store containers. This includes yard stacks, ships, trains, and trucks. These different types of stocks differ in capacity and complexity. Transport refers to the transportation of containers in either two or three dimensions. Cranes and vehicles for horizontal transport belong to this category. Transport jobs have to be allocated to them, and sequences of jobs have to be performed. The calculation of sequences is typical for the transportation means.

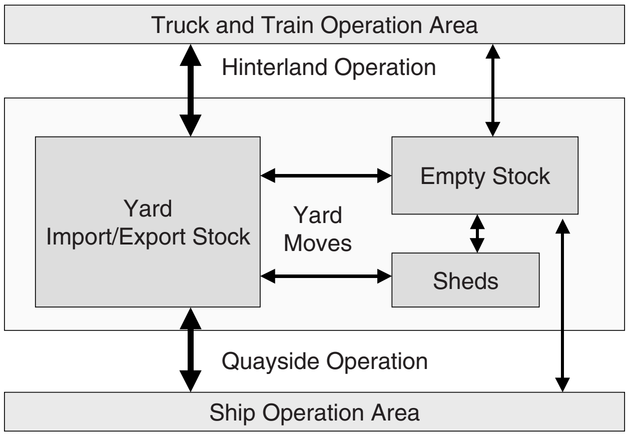


Fig. 1. Operation areas of a seaport container terminal and transport flows [136, p. 6].

(a) Large vessel at a berth with quay cranes (courtesy of Hamburger Hafen und Logistik AG – HHLA, www.hhla.de).

(b) Crane operations at a vessel (courtesy of HHLA).

Fig. 2. Vessel at a quay.

Types of Cranes

Different types of cranes are used at container terminals. Quay cranes for loading and unloading ships can be seen as a first category (Figures 2, 3(a)). A second category of cranes is applied to stacks. Here we distinguish three types of cranes: rail mounted gantry cranes (RMGs; also referred to as automated stacking cranes (ASCs)), rubber tired gantry cranes (RTG), and overhead bridge cranes (OBC). RTGs are more flexible in operation while RMGs are more stable (see Figure 4 for the difference in the wheels/tires, and Figure 5(a) for a RTG during operation). OBCs are mounted on concrete or steel pillars.

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

(a) Quay cranes (here: dual-trolley crane) serving a vessel (courtesy of HHLA).

(b) Stacking cranes (here: DRMG) serving a container block in the yard (courtesy of HHLA).

Fig. 3. Quay cranes and stacking cranes.

(a) Wheel of a RMG on rail (courtesy of Shanghai Zhenhua Port Machinery – ZPMC, www.zpmc.com).

(b) Tire of a RTG (courtesy of ZPMC).

Fig. 4. Different wheels of RMG and RTG.

block to the other are buffered in a block's transition area. Double-RMG (DRMG; Figures 3(b) and 5(b)) systems represent a rather new development. They consist of two RMGs of different height and width that are able to pass each other. A slightly higher productivity of the system is expected by avoiding a handshake area. 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 per hour. A move is defined by a complete pickup and delivery operation, i.e., a gantry crane can move approximately 20 containers into or out of a block within one hour. This handling includes the crane movements as well as the movements of the trolley etc.

(a) RTG beneath a block serving an internal truck (courtesy of ZPMC).

(b) DRMG with an AGV in front (courtesy of HHLA).

Fig. 5. RTG and DRMG.

The latest development is a Triple-RMG with two small ASCs and one wider and higher ASC, capable of passing over the smaller ones. Operating on separate sets of rail tracks, the cranes are capable of moving freely within the block. For example, by 2015 the reorganized Container Terminal Burchardkai (Hamburg) will be operated as a block system in order to nearly double its capacity.

Horizontal Transport Means

A variety of vehicles is employed for the ship-to-yard transportation and the landside operation. The transport vehicles can be classified into two different types. Active vehicles are able to lift containers by themselves while passive vehicles must be (un)loaded by either quay cranes, gantry cranes or other equipment for lifting. Trucks with trailers, multi-trailers and AGVs (Figure 6(a)) belong to the class of passive vehicles. AGVs are unmanned vehicles able to drive on a specific road network. The position of an AGV is controlled by electric wires or transponders in the ground of the network. AGVs can either load one 40-ft/45-ft container or two 20-ft containers. SCs (Figure 6(b)), forklifts, and reachstackers belong to the class of active vehicles. SCs are the most important ones amongst them. They are able to transport containers as well as to stack them in the yard. SCs are employed for (un)loading containers at the waterside, handling empty containers and delivering containers to trucks and trains. Furthermore, gantry cranes can be used for serving trains (Figure 7).

Reachstackers are shown in Figure 8(a), one is serving a waiting truck by lifting a container. External trucks waiting at a transfer point at the end of a container block are shown in Figure 8(b).

Recently a system with automated SCs (also called Automated Lifting Vehicles (ALVs)) was developed for Patrick Terminal/Brisbane, Australia. Furthermore, automated SCs with restricted height are planned for transport

(a) AGV in front of quay cranes (courtesy of HHLA).

(b) SC serving a truck (courtesy of HHLA).

Fig. 6. Horizontal transport means: AGV and SC.

(a) Crane serving a train (courtesy of HHLA).

(b) Waiting trains under a gantry crane; a reachstacker on the right (courtesy of HHLA).

Fig. 7. Transtainment with railway.

purposes only. But their ability for lifting containers allows for decoupling the work flow of transport and crane activities using buffers at the respective interfaces.

(a) Reachstackers and trucks (courtesy of HHLA).

(b) Trucks (DRMG on the right; quay cranes in the background) (courtesy of HHLA).

Fig. 8. Horizontal transport at stack interfaces.

Assisting Systems

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.

Regarding routing within terminals, the internal information and communication systems play a major role in optimizing the terminal operation. The installation of radio data communication at container terminals started in the middle of the 1980s. It is the main medium to transmit job data from the information systems to cranes and transport vehicles. Thus, it is the technical prerequisite for the implementation of operations research methods for optimizing operations. Container positioning systems based upon (Differential) Global Positioning Systems, dead-reckoning or optical based systems such as Laser Radar constitute the technical base for the improvement of yard and stacking logistics. Whenever a container is lifted or dropped, the position of the container is measured and transmitted to the terminal's information system.

3.2 Container Terminal Systems

A great variety of container terminals exists mainly depending on which types of handling equipment are combined to form an entire terminal system. All terminals use quay 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 SCs. 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, SCs, or reachstackers.

The decision on which equipment is used depends on several factors. Space restrictions, economical and historical reasons play an important role. Despite the variety of equipment combinations, two principal categories of terminals can be distinguished: pure SC systems and systems using gantry cranes for container storage. The former are often also referred to as Direct Transfer System (DTS), the latter is called an Indirect Transfer System (ITS). DTS requires a larger area due to dedicated lanes required for vehicles to access slot positions. The ITS minimizes yard area requirements. Thus, terminals in the Asia-Pacific region with very limited and expensive space typically rely on the ITS with containers stacked in compact sections and high stacks, respectively. A decision for more expensive AGVs and automated gantry cranes can be made in case of high labor costs and new terminal construction. Such systems are now in operation at the Europe Combined Terminal (ECT, Rotterdam) and at the Container Terminal Altenwerder (CTA, Hamburg). Because space is becoming a scarce resource, a tendency for higher storage is to be foreseen. These two main categories with containers being stacked on top of each other by either SCs or gantry cranes are common in Europe and Asia. A third type is an on-chassis system with containers being stored on chassis. This system is used quite often in North America. It lacks of special stacking cranes, has simpler stacking logistics and demands for more space. Its logistic aspects are covered by the other two systems.

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 SCs for the landside operation. Up to now AGV terminals only exist in combination with automatic gantry cranes. Trains are usually loaded and unloaded by gantry cranes even in case of SC terminals, although in some cases SCs are also used for this purpose (see Figures 9, 10).

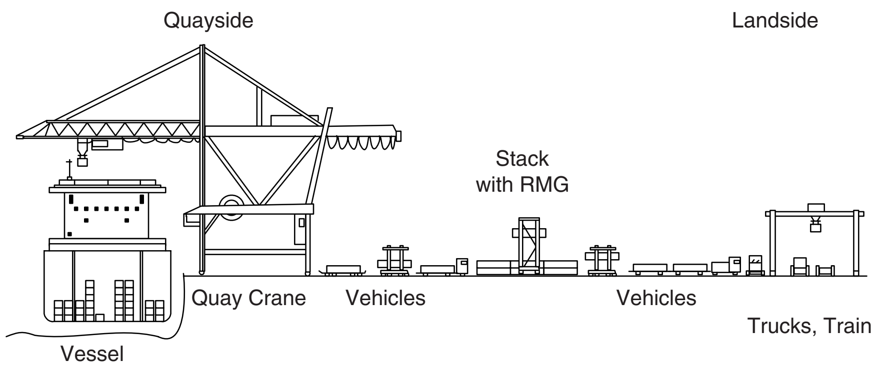
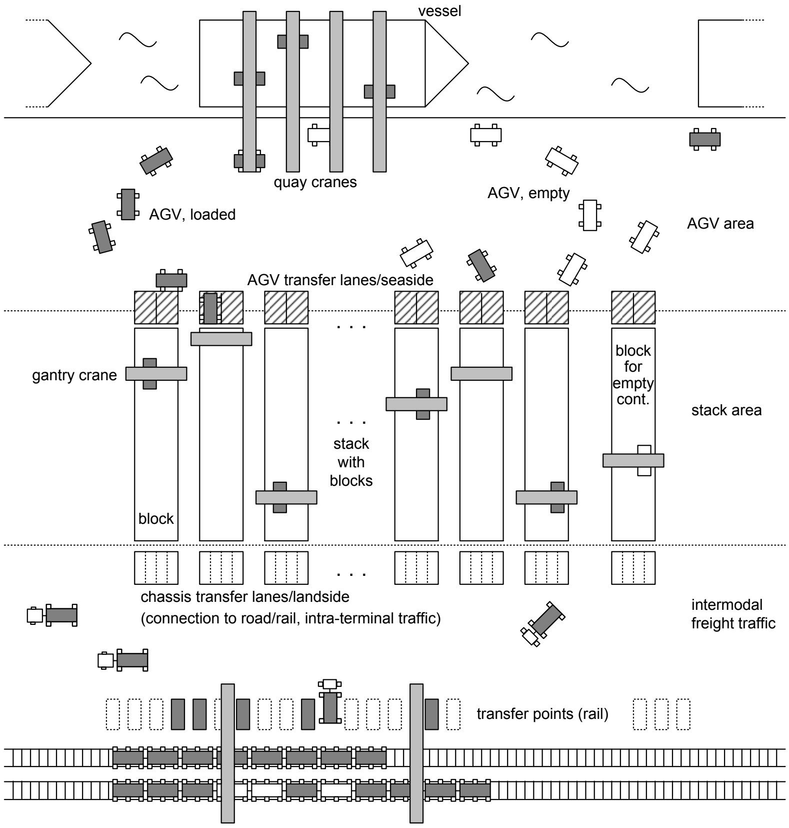


Fig. 9. Container terminal system (schematic side view, not true to size) [136, p. 13].

(a) Terminal with AGVs and DRMGs (courtesy of HHLA).



(b) Terminal layout (schematic view).

Fig. 10. Layout of an automated terminal (aerial views).

Literature Review

An ever increasing number of publications on container terminals have appeared. We refer to, e.g., [136] or [107, 126, 142].

Engineering oriented journals as well as specialized outlets, brochures, or websites of suppliers of material handling equipment and services in the container sector provide general information about technical equipment for container handling (see, e.g., http://www.porttechnology.org, http://www.kalmarind.com, http://www.zpmc.com or http://www.dakosy.de/en). For different types of cranes and their use see, e.g., [117, 134] or http://www.cranestodaymagazine.com. For an overview of handling technologies for terminal operations see, e.g., [73, 74]. Modern concepts for container storage and transportation in particular to and from terminals in order to solve capacity problems of terminals, rails and highways, such as the automated 'Freight Shuttle', 'CargoMover', 'CargoRail', 'Auto-GO', 'TransRapid for cargo' (maglev freight container movement), 'Grid RAIL', Automated Storage/Retrieval Systems (AS/RS) and others, can be found, e.g., in [3, 33, 56, 75, 101, 123, 124, 155]. The embedding of handling equipment at container terminals with respect to general aspects of innovation management is considered in [151]. For research on costs and performances of different terminal systems with vehicles such as SCs, AGVs, and ALVs, see, e.g., [125, 145, 146, 149]. Duinkerken et al. [35] compare three systems with trucks and multi-trailers, AGVs, and ALVs for overland transport between container terminals within a large area with several terminals such as Rotterdam's Maasvlakte complex. All these studies are based upon simulation experiments.

4 Routing and Scheduling at Container Terminals

In this section, as the main part of our chapter, we describe various problems related to container terminal operations. The specific problems are considered as they are related to VRPs in one way or the other. Our exposition 'starts' at the quayside and 'gradually moves' towards the landside. While some of the problems at container terminals obviously relate to vehicle routing, others do not, at least at first glance. Therefore, every subsection explains the respective problem from a terminal's perspective first. Then a literature review is provided emphasizing the specific references. This also includes the description of those specific problems as VRP or modifications.

The first two types of problems are related to ship planning which consists of three partial processes: berth planning, stowage planning and quay crane scheduling. Since the planning of a ship's stowage does not directly refer to routing problems we restrict ourselves to detailed berth and quay crane scheduling. Berth scheduling and quay-crane allocation problems are related since the number of quay cranes assigned to a vessel has impact on the ship's berthing duration. Nevertheless, due to the complexity of the integrated problem, most studies treat the two issues separately.

Moreover, as mentioned before, two types of transport can be distinguished at a container terminal: the vertical stacking performed by crane-like vehicles and the horizontal transport performed by AGVs, SCs, ASCs, trucks or (multi-)trailers. The horizontal transport subdivides into the quayside and the landside transport serving ships or trucks and trains, respectively.

4.1 Berth Scheduling

Berth scheduling or berth allocation is the process of determining the time and position at which arriving vessels will berth. Before arrival of a ship, a berth has to be allocated to the ship. The schedules of large overseas vessels are known about one year in advance. 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. Technical data of ships and quay cranes have to be considered. All ships to be moored during the respective time period have to be reflected in berth allocation systems. A typical objective of berth allocation (which in fact impacts or implies routing problems) is the minimization of the total sum of shore to yard distances for all containers to be loaded and unloaded. Another closely related objective is the minimization of distances traveled by the means of transportation (e.g., SCs) serving the quay cranes. This corresponds to maximum productivity of ship operation. Automatic and optimized berth allocation is especially important in case of ship delays.

Berth planning problems may be formulated as different combinatorial optimization problems depending on the specific objectives and restrictions that have to be observed. For example, berth planning can be modeled by means of the resource constrained project scheduling problem, as a discrete resource allocation problem, as Multi-Depot VRP with Time Windows (MDVRPTW) or as a type of continuous line partitioning problem. A drawback of considering a berth as a collection of discrete berthing locations is that the number of ships that may be served simultaneously is fixed regardless of ship lengths. The continuous representation does not have this limitation: for the same length of berth, more vessels can be served simultaneously if they are shorter. However, the continuous case requires determining the exact berthing position of each ship as a real-valued position on a continuous line. Moreover, the berthing time for each ship must be determined simultaneously. Restrictions can reflect special equipment that is needed for certain operations, as it is the case, e.g., for unavailability due to maintenance or for Roll-On/Roll-Off-ships where tractor trailers drive into the ship.

Literature Review

Early studies on allocating berths to military vessels propose priority rules, simulation approaches and mathematical models (see, e.g., [17]). Connections of berth planning to assignment problems and especially to the quadratic semi-assignment problem are emphasized in [63]. Due to the large interdependency, berth and yard planning are frequently considered in a common optimization model (see, e.g., [18, 40, 137]).

Cordeau et al. [27] present a tabu search algorithm for solving the berth allocation problem. The model of [68, 70] is considered as well as the formulation as a MDVRPTW. In the MDVRPTW ships represent customers. They are modeled as vertices in a multigraph. Service time windows on the ships are expressed by imposing time windows on those vertices. A berth is seen as a depot that is divided into an origin vertex and a destination vertex. Time windows on those vertices correspond to the availability period of a berth. There is one vehicle for each depot. A tour of a vehicle starts and ends at the vehicle's depot. The objective is to minimize the weighted sum of service times.

For additional references dealing with berth planning see, e.g., [68–70]. For an up-to-date literature review see [67, 71, 136] or see [30] for an overview with regard to intermodal transportation.

4.2 Quay Crane Scheduling

Quay crane allocation and scheduling is the process of determining quay cranes serving a vessel as well as the time and sequence of loading and unloading movements of quay cranes assigned to holds of a berthing vessel. This crane split has to reflect several constraints – especially technical data of cranes and ships moored at a berth in a given period and the accessibility of cranes at a berth. The number of cranes operable at one berth in general is restricted because not every crane can be driven to every berth. Furthermore, idle times are caused by interferences due to spatial constraints, since the quay cranes are mounted on the same track and cannot cross each other. Only one quay crane can work on a hold at any time. A minimum safety distance (usually at least two ship bays) must be maintained between two adjacent quay cranes and their jibs, respectively.

There is no unique objective for optimization. In terminal practice it depends on the actual 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 main modes of loading. Stowage plan, crane split, and mode of loading together result in a working instruction defining the loading sequence for every container of a bay. The routing sequences for the landside transport have to match this loading sequence.

In general, research focuses on two types of quay-crane scheduling problems. In the first type, schedules for berth and quay cranes are simultaneously defined by specifying the start and end times of (un)loading operations for each quay crane assigned to a specific ship. Most studies address the second type determining detailed schedules for each quay crane with pre-specified time windows for (un)loading operations at assigned vessels. The formulation of both problem types is usually based upon mixed-integer programming (MIP) models.

Literature Review

Kim and Park [83] propose a branch and bound algorithm and a greedy randomized adaptive search procedure (GRASP) to solve the quay crane scheduling/load sequencing problem. The objective is the minimization of the weighted sum of the makespan of the container vessel and the total completion time of all quay cranes. Contrary to Peterkofsky and Daganzo [120] Kim and Park separate the detailed crane scheduling problem from the berth-scheduling problem in order to address the quay crane scheduling problem at a more detailed level by taking non-interference constraints into account. However, the problem is restricted to a single vessel only. Computational complexity of the studied problem is not discussed.

Non-interference constraints are taken into account in early studies conducted by Lim et al. [97] and Zhu and Lim [156] (see also [98–100] as well as [157]). In [97] the problem is modeled as bipartite graph matching problem taking cranes and jobs as vertices and defining the weights of connecting edges as crane-to-job throughput. A dynamic programming algorithm is given to solve problems with simple spatial constraints in order to find a static crane-to-job matching with maximum throughput. Furthermore, the problem is extended towards considering more complex constraints. This $\mathcal{NP}$-complete problem is solved by a probabilistic tabu search and a squeaky wheel optimization with local search. Since the model is based upon a 'profit value' of a job which is difficult to define in practice, the implementation of the study in real-world terminals seems to be difficult. Furthermore, precedence constraints between tasks are not considered. The study is augmented in [157] with regard to real-world practice aiming at completion of all the jobs with respect to certain criteria instead of only maximizing the total throughput without taking time into consideration. Thus, the objective is to minimize the latest completion time of all the (non-preemptive) jobs, which come in different sizes.

Ng and Mak [113] propose a heuristic for solving the quay crane scheduling problem. The problem is decomposed by partitioning the ship into non-overlapping zones. The resulting subproblems for each possible partition can be solved optimally by a simple rule. Tight lower bounds are found by enhancing a known algorithm. Typical terminal operations data are used to generate a set of test problems for evaluation of the heuristic algorithm's performance. The heuristic solutions are on average 4.8 % above their lower bounds.

Moccia et al. [104] mention the difference between the time precedence constraint of the quay crane scheduling problem and the route precedence constraint in the PDP or the Dial-a-Ride Problem (DARP). They formulate the quay crane problem as VRP with side constraints including precedence relationships between vertices. The problem formulation strengthens the model of Kim and Park [83]. The objective is to minimize the completion time of a vessel and the idle times of cranes caused by crane interferences. Large problem instances can be solved with the proposed branch-and-cut algorithm. Several families of valid inequalities are inserted for taking advantage of the precedence constraints between vertices. The paper indicates that the developed algorithm outperforms the algorithm proposed in [83].

Lee et al. [91], stimulated from [83], study quay crane scheduling taking non-interference constraints into account. The objective is the minimization of the makespan of handling one single container vessel (i.e., the latest completion time among all holds). The proposed genetic algorithm (GA) obtains near optimal solutions for the MIP model and shows efficient and effective performance in computational experiments.

Some new ports have begun to use a dual cycle strategy for operations of quay cranes based on experience. Only few scientific studies on dual (or double) cycling of quay cranes are published. Studies conducted by Goodchild [43–45] and Goodchild and Daganzo [46–48], respectively, are the first ones. They provide upper and lower bounds of the dual cycle model. Compared to single cycle mode, the dual cycle operation doubles the number of quay crane tasks in a cycle by allowing to carry a container while moving from the apron to the ship (loading move) as well as from the ship to the apron (unloading move). Thus, empty moves of the single cycle mode are used for carrying a container as well. The problem is formulated as a two-machine flow shop scheduling problem assuming that one quay crane consists of two separate cranes, one for loading, the other for unloading. This strategy aims at minimizing a ship's turnaround time by improvement of efficiency and increase of throughput. Even with constraints due to hatch covers the strategy can lead to a gain in productivity and a higher utilization of the expensive quay cranes. The strategy is a low cost method for increasing capacity since no additional infrastructure is required.

Zhang and Kim [154] reformulate the dual cycle scheduling problem as MIP model with additional focus on twin lift activities, i.e. the handling of two 20-ft containers at the same time (instead of one 40-ft container; the newest development are cranes able to lift two 40-ft containers, see, e.g., www.zpmc.com). The general problem is decomposed in order to account for real situations regarding to hatch covers. The approach differentiates between an inter-stage sequencing (hatch sequencing) and an intra-stage sequencing, i.e. the sequencing of crane tasks in the same hatch. The model is solved by a suggested heuristic algorithm hybridizing a gap-based neighborhood local search technique. Numerical experiments are conducted with five real cases from Busan for showing effectiveness of the approach. Optimal solutions are found in some cases. Current real scheduling solutions in the Busan port are greatly outperformed. Future research will focus on enhancing the approach by considering multi quay cranes with interference constraints.

4.3 Horizontal Transport at the Quayside

For ship (un)loading containers have to be transported from the stack to the ship and vice versa. Transport optimization at the quayside aims at reducing transport times as well as synchronizing the transports with the activities of the quay cranes. A general aim is to enhance crane productivity. While technical data of the cranes allow for a performance of 50–60 boxes per hour the real performance at operation is only in the range of 22–30 boxes per hour. This reduction is caused by unproductive times like breaks during shifts, moves of hatch covers and lashing equipment, technical or operational disturbances and congestions occurring for the horizontal transport. A gain in productivity cannot be necessarily achieved by increasing the fleet's size or speeding up transport vehicles, because the number of congestions at the cranes and in the yard increases more than proportionally. Additionally, more vehicles induce more costs and reduce economic efficiency of ship operation. Hence, an optimization system has to cope with the minimization of congestions.

At the quayside, different modes of transport and strategies of allocation of vehicles to cranes can be distinguished. 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, thus combining the transports of export and import containers. Additionally, transport vehicles can either be allocated exclusively to one crane (gang structure) or to several cranes and ships (pooling).

Depending on the mode, different potential for transport optimization arises. The single-cycle mode for import containers does not offer optimization opportunities, but export loading can be optimized at the transport level. In general, the transport sequence differs from the loading sequence which is determined by the stowage plan, the crane split and the crane's loading strategy. The transport sequence has to reflect different distances, yard reshuffles and special containers. 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. The dual-cycle is more complex since the allocation of transport vehicles to cranes is not fixed. But operating vehicles in a pool for serving several cranes in loading or discharging modes is more efficient. This mode reduces empty distances and transportation times. Furthermore, crane waiting times can be reduced if containers can be buffered under the crane's portal.

In terminal practice, automatic transport vehicles are always pooled whereas manned equipment usually operates at one crane (fixed allocation). If the loading capacity exceeds one container a multiple load mode is possible. Multiple load for AGVs offers potential for optimization. But in practice, it rarely occurs because it is difficult to organize. A main task of the control system is to synchronize manned and automated equipment in a way that the containers arrive 'in-time' at the equipments' interfaces in order to minimize the idle times of the cranes (lateness of container deliveries for the cranes) and the travel times of the transport vehicles. Due to the ship operations' dynamic, online optimization is necessary. Often the (un)loading sequence must be altered immediately, forced by disturbances in operation as result of technical problems with quay cranes or horizontal transport vehicles or due to crane driver's ad hoc decisions. Such reasons force (re)calculating sequences only for few containers. However, since AGVs run slower than yard trailers, the fleet size of AGVs is usually larger than the fleet size of yard trailers in order to avoid bottlenecks. Therefore, heavy AGV traffic is produced. Proper handling of AGV traffic is crucial for efficient container handling.

Literature Review

Automated Guided Vehicles

The number of references for AGVs is enormous as AGVs are commonly used in warehouse operations and flexible manufacturing systems (see, e.g., [121] for a survey of scheduling and routing algorithms for AGVs and classification of algorithms, or more recently [61, 62, 92]).

Vis et al. [148] determine the fleet size of AGVs with a heuristic based upon the maximum flow problem. The underlying flow network is based upon the defined time when a transfer job takes place for moving a container from one place to another. Since the network will become very large in real-world environments this job definition seems to be inapplicable. Another disadvantage is the restriction to single-trailers with only unit capacity (see, e.g., [116] for an extended yard trailer routing). Multi-trailers with capacity of more than one container are seen at modern terminals (such as the ECT, Rotterdam). Similar to [148], Bish [8] aims at minimizing the turnaround time of ships by means of dynamic job assignment to AGVs.

Kim and Bae [78] suggest a network-based MIP model for AGV dispatching and provide a heuristic algorithm. The objective is the minimization of the total idle time of a quay crane resulting from late arrivals of AGVs as well as the associated total travel time. It is assumed that storage locations of containers and schedules for (un)loading operations by quay cranes are given. An extended approach with a pooled dispatching strategy taking multiple quay cranes and dual-cycle operations of AGVs into account is proposed in [4, 79].

Grunow et al. [49, 50] 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, an MIP model 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 [128]. In [51] a scalable simulation model is used for investigation and evaluation of dispatching strategies. The developed pattern-based off-line heuristic with dual-load AGVs outperforms conventional on-line heuristics adopted from flexible manufacturing systems.

Möhring et al. [105] propose a real-time algorithm for routing AGVs. Collisions, deadlocks and livelocks are avoided at the time of route calculation. The approach is based upon the determination of a shortest path with time windows for each request and a subsequent readjustment of the time windows. Computation times for the conflict-free routing are appropriate for real-time applications. In terms of overall transit times the algorithm is superior to a static approach used at the CTA (Hamburg), in particular for scenarios with many AGVs causing heavy traffic.

Briskorn et al. [15,16] propose a dispatching strategy for AGVs with a job-vehicle assignment that is based upon a model formulation with rough analogy to inventory management. The problem can be solved exactly. A simulation study shows higher productivity at a terminal applying this strategy compared to conventional due-date-based strategies.

Current research on deadlock handling at automated container terminals can be found in [80, 93]. In the former paper, Kim et al. propose an efficient algorithm for deadlock prediction and prevention in AGV systems. The approach guarantees deadlock-free schedules for AGVs to cross the same area at the same time. The method is evaluated in a simulation study showing satisfactory results. Average speed of vehicles, space utilization and computational time imply potential for the method to be used in practice. Since common literature focuses on deadlocks only with regard to routing of AGVs and their guide path, Lehmann et al. [93] address blocking effects between vehicles and handling units. They conduct a comprehensive simulation study. It shows the suitability of different methods for detection and resolution of deadlocks occurring in the phase of resource assignment. The proposed deadlock-handling scheme is seen as 'a first step towards integrated scheduling and dispatching approaches for equipment units in highly automated container terminals.' The approach with resolving deadlocks rather than entirely avoiding them is preferred as being 'the most appropriate alternative, as more conservative approaches would result in lower equipment utilization.' It is pointed out, that the implementation of the proposed methods into the logistics control software of automated terminals is necessary (if not economically viable) in order to avoid a downtime of an entire terminal.

Duinkerken et al. [36] compare different trajectory planning strategies for AGVs by means of simulation. Experiments show high potential for a dynamic free ranging approach that improves the system's transport capacity.

Straddle Carriers

Obvious routing problems at container terminals are present in SC operations. Since SCs are engaged in different types of complicated container handling, their efficient routing is achieved by minimization of empty runs. Only a few papers address the routing problem regarding SCs.

Steenken [133] and Steenken et al. [135] examine the routing of multiple SCs working on tasks with time windows. The problem is similar to the yard trailer routing problem addressed in [116] since multiple tours are formed in both problems. However, the SC routing is much simpler due to the single capacity of a SC. The objective is the minimization of empty-travel distances. Different algorithmic approaches known from machine scheduling and solving the TSP, RPP, etc., respectively, are examined. In [133] the problem is modeled and solved as a linear assignment problem combining movements for export and import containers. The percentage of the number of empty drives is reduced from 41 % to 28 %. A model calculation shows savings of 14.5 % in empty-travel distances. In [135] the problem is formulated as a network problem with minimum costs. Considerable gains of productivity can be obtained as well as savings of $20 - 35$ % in empty-travel distances. Furthermore, results and the architecture of an implementation are presented in [134]. All jobs for truck, rail and yard operations are optimized by a hinterland routing system. A master routine integrates these different working areas and dynamically determines the number of SCs taking the current job volume and workload in each area into account. A gain in productivity of about 50 % is reported as well as a reduction of the control staff from 10 to 2 employees per shift.

Kim and Kim [82, 86] propose a routing algorithm for a single SC loading export containers out of the stack onto waiting yard trailers. The approach is basically the same to their studies regarding transfer cranes [81, 85] (see p. 576). It is assumed that a single SC is used and that the work schedule for a quay crane is already given. The objective is the minimization of a SC's container handling time by minimizing its total travel distance. In [86] the number of containers to be picked up at each yard bay is determined in a first stage. The optimal sequence of yard bays to be visited by the SC is found in a second stage. This optimal route of a SC is determined by dynamic programming. In [82] a beam search heuristic is used for determining the routing of a single SC. The performance of the algorithm is tested by solving 360 sample problems with different number of blocks used for all containers of a vessel (degree of dispersion of containers in a yard) and different number of partial-tours in a work schedule. Furthermore, the results are compared with the optimal solutions for seven examples with an average objective value being 14.3 % above the corresponding optimal objective value. A practical example with two SCs is also solved. The extension to multiple SCs and sequencing of individual containers is identified as promising topic for further research. Additional constraints from real-world loading operations have to be considered.

Kim and Kim [87] summarize the problem and solution approaches of [82, 86] as well as of [81, 85] for general yard-side equipment such as SCs and gantry cranes. Their experiments show that the proposed beam search algorithm outperforms a GA. The pick-up sequence for individual containers in a bay remains undetermined.

Thurston and Hu [139] provide an agent based approach focusing on the quayside operations. It is assumed that the discharge of a vessel has to be completed before the loading operations can start. The approach provides insight into job assignments and routing for SCs. The system is evaluated in a simulation experiment based upon random data.

Das and Spasovic [31] present a scheduling procedure for SCs. An assignment algorithm dynamically matches SCs and trucks as each become available. The objective is the minimization of empty travels and delays in servicing customers. The superiority of the proposed procedure over two alternative scheduling strategies is shown by tests with a simulation model of a real-world system (New York/New Jersey).

Böse et al. [12] investigate different dispatching strategies for SCs to gantry cranes in order to reduce delays of quay cranes and, therefore, the vessel's turnaround time at port by maximizing productivity of gantry cranes achieved by an efficient schedule of given SCs. Pooling of SCs and double-cycle mode of carriers are considered. Storage locations of containers are assumed to be given. Thus, the problem is to assign delivery tasks of (un)loading containers to SCs, basically the same as proposed by Kim and Bae [79] but without considering travel times of vehicles. The allocation problems are solved using evolutionary algorithms in computational experiments based upon real data (without taking stochastic influence into account). Considering an online optimization setting, numerical results for real data may show that the number of sequenced containers need not have a large influence when the carriers operate in double cycle mode [102].

Nguyen and Kim [115] discuss the dispatching of ALVs. Information about locations and times of future delivery tasks is utilized in an MIP model aiming at an optimal assignment of delivery tasks to ALVs. The $\mathcal{NP}$-hard problem is formulated as a scheduling problem with precedence and buffer constraints similar to the multiple TSP with precedence constraints and time windows.

4.4 Horizontal Transport at the Landside

The landside transport incorporates rail operation, truck operation and internal transports. A simple strategy is to allocate a given number of vehicles to each operation sphere appropriate to the workload expected. A more advanced strategy is the pooling of vehicles for all these working areas.

Trains are commonly operated by gantry cranes while the transports between the stack and the railhead are performed by SCs, trucks and trailers or similar equipment. Containers are buffered alongside the railhead or on trailers. Sometimes pure SC operation with SCs driving over the wagons can be observed.

Operation at the railhead is analogous to the quayside operation. 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, the crane waiting times as well as the empty transport distances of cranes and transport vehicles by synchronization of the equipment (in particular in the complex dual-cycle mode). Based upon a stowage instruction indicating wagon positions for container attributes, the yard situation can be reflected.

Trucks arrive at the terminal's in-gate. Data of the containers are fed in the terminal's information system. Trucks then drive to transition points for being served by terminal's equipment. Large container terminals serve some thousand trucks a day. 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. Hence, transport jobs for the internal equipment cannot be released until the truck arrives at the transition point. Optimization has to be very flexible and fast, online optimization is necessary. Objectives at the truck operation area are minimization of empty distances and travel times. 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.

Some of the above mentioned problems are generally addressed in the truck and trailer (or tractor-trailer) vehicle routing problem (TTVRP). Three subclasses of VRP are similar to the TTVRP: the VRP with time windows (VRPTW; for some recent publications see, e.g., [13, 14]), the vehicle scheduling problems (VSP; see, e.g., [5, 152]) as well as the truck and trailer routing problem (TTRP; see, e.g., [20]).

The TTRP is an extension of the basis VRP occurring in many real-life applications. It involves pickup and delivery processes and has characteristics of the VRP with backhauls (VRPB) (see, e.g., [144]). It is a multi-level optimization problem combining a pure truck route, a pure vehicle route and a complete vehicle route. The latter consists of a main tour traveled by a complete vehicle (truck and trailer) and one or more sub-tours traveled by a truck alone. A sub-tour starts from and returns to a customer found on the main tour. The trailer is parked at this customer during the truck's sub-tour. 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.

Unlike the VRPTW, the TTVRP incorporates limitations in resources of trailers and outsourcing of jobs. Despite analogous concepts of a trip in the VSP (consisting of a pair of source and destination, each defined by starting and ending time) and a job in the TTVRP, the VSP does not take trailer type constraints into account. In the VSP, a customer can be visited more than once or not at all, contrary to the VRP assumptions. In the TTVRP, trucks have to visit trailer exchange points in order to pick up the correct trailer type depending on the current job to be serviced. This approach is different from the TTRP. Furthermore, the TTRP does not allow outsourcing of jobs to external companies.

Literature Review

While the basic VRP and lots of variants have attracted the attention of many researchers, only a few papers are focused on problems with trucks and trailers (see, e.g., [20, 41, 127, 129, 138]). To the best of our knowledge the number of papers focusing on trucks and trailers at container terminals is very limited.

Chao [20] tests a tabu search method for improving solutions that are initially found by a construction method. Twenty-one TTRP instances are considered based upon seven basic VRPs from the well known CMT-set of test problems [26]. They differ in the number of customers, the number of trucks and trailers and their capacities as well as the ratio of demand to capacity. The objective is to minimize the total distance traveled, or to minimize the total cost incurred by the fleet. The solution construction approach consists of three steps: the relaxed generalized assignment of customers to one of the three types of routes, the route construction using a cheapest insertion TSP heuristic [11] and a descent improvement with four sub-steps. The proposed tabu search with a frequency-based tabu restriction is coupled with the deviation concept from deterministic annealing. It aims at improvement of the initial solution of the construction step. Furthermore, a new type of tabu restriction is developed in order to implement intensification and diversification strategies for accentuating and broadening the search in the solution space. The computational experiments indicate that the proposed methods can solve the TTRP 'consistently, effectively and efficiently'.

Nishimura et al. [116] propose a trailer assignment method for solving the dynamic trailer routing problem at container terminals where yard trailers are normally assigned to specific quay cranes until the work is completed. The paper shows a new dynamic routing scheme for saving yard operation time and container handling costs. The paper examines the problem of pickup and delivery with multiple tours being independent and not connected at a depot (like in the standard PDP). The trailer routing is defined with a given set of calling vessels. A new routing decision is made when a ship changes its operation task, i.e. starts loading or discharging. A fleet of trailers has a set of tours connecting quay cranes and stack points in the yard. A static tour is a shuttle transit between waterside and landside transfer location. For example, a single-trailer picks up a container at a quay crane in discharging and delivers it to an assigned stack area for unloaded containers and finally returns to the quay crane. A trailer's usage is much more flexible in a dynamic tour with moving the trailer to a different unloading quay crane than before or to a stack area for export containers in order to transport a container to a quay crane in loading operation. The most flexible itineraries with mixtures of pickup and delivery can be achieved with multi-trailers in dynamic tours. Computational experiments on test data show that the dynamic trailer assignment is superior to the static version in terms of capital and operating terminal costs. The fleet size can be reduced due to shorter empty travel distance of trailers. The dynamic assignment principle is suggested to be implemented for both tactical and operational decisions within terminal management. For planning new terminals, ship handling and trailer routing can be simulated in order to determine the trailer fleet size. Simulation of trailer movements can also be useful for stevedoring companies making up a daily/weekly trailer work schedule given a prospective cargo handling profile. A drawback is the complexity of the itineraries. Errors of trailer drivers may increase. Otherwise, these types of errors may be reduced with application of modern communication and tracking systems.

Koo et al. [88] focus on a special problem occurring at Busan with its very limited terminal area. A large number of containers is moved between on-dock container yard and off-dock yard by truck causing tremendous traffic problems in the city as well as increasing logistic costs. The paper deals with a static transportation problem with all transportation jobs being ready to be picked up at the beginning of the planning horizon. Travel times and (un)loading times are deterministic and known in advance as well as the number of containers to be moved. The environment is referred to as a tractor-trailer transportation system or a static DARP with multiple vehicles of single capacity, similar to the PDP with sequence dependency. The goal is to find the smallest required fleet size and a route for each vehicle to fulfill all transportation requirements within the static planning horizon. A two-phase fleet sizing and vehicle routing procedure incorporating a tabu search is presented. A computational study shows solutions of good quality in comparison with two other existing methods.

Ng and Mak [110] propose an algorithm for sequencing trucks that have to enter the working lane adjacent to a yard block with export containers. The objective of this approach is to reduce congestions of the working lane by minimization of the total time required to serve all empty trucks that are dispatched to a yard block.

Ng et al. [114] address the problem of scheduling a fleet of trucks at a terminal in order to minimize the makespan. The trucks have to perform a set of transportation jobs with sequence-dependent processing times and different ready times. The formulated $\mathcal{NP}$-hard MIP problem is solved by use of a GA. The GA's performance is enhanced by incorporating instance-specific information in the search process. In the truck scheduling problem, the travel time between two locations, the truck's ready time, the job's ready time, and the duration of each job are taken into account. Useful information is inherited by a developed greedy crossover scheme aiming at reduction of computational effort. This novel scheme is tested against six popular schemes which have been shown in other studies to be effective for solving parallel machine scheduling problems, VRPs, and the TSP (partially mapped crossover, order crossover, position-based crossover, order-based crossover, a fast union crossover called 'union crossover #2', and enhanced edge crossover). The performance of the crossover schemes is evaluated by solving a set of randomly generated test problems based on real terminal operations data. Therefore, the test data reflect typical technical figures, e.g., a truck speed of 15 km/h, 2 minutes handling time for a quay crane per container, 4 minutes for a yard crane etc. The new GA's solutions are on average 4.05 % better than the best solutions of the other six GAs.

4.5 Transport by Stacker Cranes

Optimization of transports performed by gantry cranes operating in stacks focuses on sequencing of jobs and their assignment to the respective crane. Priority of jobs have to be taken into account. Transport optimization for stacker cranes reduces to the same requirements as for the horizontal transport. Comparative algorithms can be applied. A common objective is the minimization of the waiting times of the transport vehicles at the stack or bay interfaces and the travel times of the cranes. Crane operations at the stack and operations at the quayside or landside are interdependent. Since 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

Only a few papers address the routing problem regarding gantry cranes at stacks within container terminals.

Kim and Kim [85] propose an algorithm for a single gantry crane loading export containers out of the stack onto waiting yard trucks. The load plan (a number of sequences of containers that have to be picked up together) and the bay plan (mapping of the physical location of containers in the stack yard) are taken into account. The objective is the minimization of the crane's total transfer time including set-up time at each yard bay and travel times between consecutive yard bays. It is assumed that a single transfer crane is used and that all containers for loading are located in one block or adjacent blocks in the travel direction. The MIP formulation is solved by decomposing the problem into a transportation problem and a sequencing problem. It is proven that it is sufficient to solve the sequencing problem only for the basic feasible solutions of the transportation problem. The basic feasible solution with the minimum cost is selected. 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. It is stated that the developed algorithm may solve problems of practical size within several seconds efficiently. Neither complexity of the problem nor computational results are discussed in the paper. The same algorithm is used for solving the MIP of a 'practical problem of a moderate size' in a more detailed paper [81]. The load sequence of individual containers within a specific bay remains undetermined. It is pointed out that the examined load planning problem is different from similar problems like, e.g., routing of a manual picker within a simple warehouse (see, e.g., [42, 55, 122]), TSP or VRP because the crane is allowed to revisit a yard bay multiple times. Furthermore, the number of containers to be picked up at each visited bay has to be determined in addition to the visiting sequence of the bays. The authors published similar papers with regard to SCs [82, 86] (see p. 571).

Ng and Mak [111, 112] address the problem of scheduling a yard crane performing a given set of (un)loading jobs with different ready times. The objective is the minimization of the sum of job waiting times. A branch and bound algorithm is proposed for solving the $\mathcal{NP}$-complete problem.

Most papers focus on operations of a single crane. Routing or scheduling algorithms for multiple cranes are hardly addressed in literature.

A simulation study on operational rules for DRMGs is shortly discussed by Kim et al. [84]. 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.

DRMGs are also examined in [37]. Solution approaches are developed for specific sequencing and scheduling problems in order to take advantage of using the two cranes being able to overtake each other and increase the terminal's throughput. Different priority rules are tested in simulation experiments.

Saanen et al. [126] compare three different configurations with RMGs: the single RMG, the DRMG and the twin RMG (with two separated RMGs, one serving the waterside, the other serving the landside). They simulate different stacking alternatives and evaluate throughput, flexibility, complexity, operational cost and investment cost. Overall, the DRMG appears to be the best performing one, but it needs the highest amount of space.

Ng [109] studies the problem of scheduling multiple yard cranes in order to minimize the sum of truck waiting times in a yard zone. The problem is similar to the problem of scheduling DRMGs due to inter-crane interference with blocked cranes to be avoided. But it is not identical since DRMGs can pass each other on separated lanes, whereas in [109] two or even more yard cranes share a single bi-directional traveling lane in a yard zone. The $\mathcal{NP}$-complete scheduling problem is modeled as an integer program. A dynamic programming-based heuristic and an algorithm to find lower bounds for benchmarking the heuristic's schedules are developed. Computational experiments show effectiveness of the heuristic, providing solutions on average 7.3 % above their lower bounds. In [109] it is stated that 'it is clear from the literature review that no studies have been conducted on scheduling of multiple yard cranes. Given the importance of yard crane operations on a terminal's productivity, effective yard crane schedules are needed.'

Lee et al. [90] propose a simulated annealing algorithm for solving the problem of scheduling two yard cranes. The two gantry cranes serve the loading operations of one quay crane at two different container blocks by picking up a desired container from a container block and loading it onto a yard truck waiting aside the block. The model aims at the minimization of the total loading time at the stack area. The schedule determines the container bay visiting sequences and the number of containers picked up simultaneously. Computational experiments show that the completion time found by the proposed algorithm is on average 10.03 % above the lower bound.

5 Conclusion and Outlook

The importance of optimizing logistic operations at seaport container terminals is reflected in an increasing number of theoretically and practically oriented papers during the last decade. Research addresses more or less all elements of the transport chain within a terminal as well as outside a terminal, with regard to assignment problems as well as routing and scheduling problems. As we have seen in this chapter, various problems related to container terminal operations come along as vehicle routing problems, either directly or in disguise.

All planning levels, strategic, tactical, and operational are taken into account. Modern information and communication technology enables the application of optimization methods in different areas of real terminals. However, the specific characteristics of a container terminal usually hinder a direct application of models being abundant in standard literature and demand for model adjustments.

High investments and high operating costs for ships and port equipments as well as severe and increasing competition between container terminals force operators to reduce unproductive demurrage at the port. Furthermore, a new challenge is the handling of upcoming mega-containerships with a capacity of more than 10,000 TEU. Keys to efficiency seem to be the automation of in-yard transportation, storing and stacking as well as the application of optimization methods. The application of mechanisms for intelligent routing and scheduling of vehicles is part of this strategy and allows for economic utilization of expensive equipment and space. Furthermore, a terminal's competitiveness includes issues of waterside operations and internal logistics as well as landside operations, transport connection and routing within the surrounding area.

Currently, most of the literature focuses on separated problems at a terminal, and mathematical models abstract from the entire transport chain and an intermodal network. For example, the crane split is modeled and crane operation is optimized without taking horizontal transport into account. But an integrated view may show, that the optimal crane split provokes congestions since the transport vehicles cannot access the cranes easily. Nevertheless, despite simplifications the models of restricted problems often remain quite complex. Without any doubt, they provide valuable insight and understanding of handling processes and problems within the entire system of a container terminal. While the need for holistic approaches and integrated optimization of operations in different terminal areas is identified, it is extremely difficult to solve real-world problems due to their complexity. Solving integrated models is beyond today's computing capability. Therefore, decomposing the problem into several related smaller models is a common approach (see, e.g., [9]). Murty et al. [107] propose an approach with an integrative decision support system. Up to now there are only a few studies on integrated problems. For example, Park and Kim [119] present an integrated approach with regard to berth scheduling and quay crane allocation. Furthermore, multi-agent system approaches with several agents representing different operation areas and equipment are presented, e.g., by Meersmans and Wagelmans [103], Thurston and Hu [139], Henesey et al. [60], or Franz et al. [39]. Veenstra et al. [143] analyze economic aspects of a container terminal simulation. The simulation concepts help to display the interdependence of different decisions and can be used to gain insight into their influence on the overall performance of a terminal. Future research will focus on the integration of advanced operational and financial strategies like dynamic pricing into their prototypic simulator. Ottjes et al. [118] focus on the integrated design and evaluation of a set of interacting terminals (multiterminal systems) and propose a generic simulation model structure. The approach has been applied to the existing and future terminals in the Rotterdam port area. Chen et al. [21] propose a tabu search algorithm for the integrated scheduling problem of various kinds of container handling equipment. The objective is to minimize the makespan regarding handling a given set of vessels.

The objective of increased terminal performance demands for increased investigation of integrated optimization. Novel equipment, e.g. the Triple-RMG as well as cranes with twin-lift operation, or handling concepts for the container terminal of the future such as the floating crane [2], floating quay [1] or offshore container terminals must be complemented with software for optimized control in order to obtain the desired and expected gain in productivity. The need for online optimization is challenging as well.

Interesting components of an integrated approach may be methods receiving less consideration in container terminal oriented literature so far. Up to now, the problem of stochasticity is usually tackled by simulation. Additionally, stochastic optimization as well as scenario based planning may be fruitful research areas. The focus on extended variants of the VRP including essential aspects of real-world problems (referred to as Rich VRP; see, e.g., [57, 59]) could be a rewarding attempt. For instance, approaches such as VRP with time windows and stochastic travel times or with stochastic customers (see, e.g., [7, 153]) may be useful and applicable at container terminals. It seems to be helpful for future research to have test and benchmark data for simulation models as well as for optimization algorithms (see, e.g., [58]).

References

1. Anonymous. The container terminal of the future, 2006. http://www.tudelft.nl/live/pagina.jsp?id=412f9f1f-8578-4b91-8760-f5a41aa5fa0c&lang=en– last check of URL: Jan 15, 2007.
2. Anonymous. The floating container crane concept, 2006. http://www.cranestodaymagazine.com/story.asp?sectionCode=66&storyCode=2040221 – last check of URL: Jan 15, 2007.
3. A. Asef-Vaziri and B. Khoshnevis. Automated technologies in maritime container terminals, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/Asef-Vaziri.pdf – last check of URL: April 19, 2007.
4. J.W. Bae and K.H. Kim. A pooled dispatching strategy for automated guided vehicles in port container terminals. *International Journal of Management Science*, 6:47–67, 2000.
5. F. Baita, R. Pesenti, W. Ukovich, and D. Favaretto. A comparison of different solution approaches to the vehicle scheduling problem in a practical case. *Computers & Operations Research*, 27:1249–1269, 2000.
6. M. Ball and M. Magazine. Sequencing of insertions in printed circuit board assembly. *Operations Research*, 36:192–201, 1988.
7. R.W. Bent and P. van Hentenryck. Scenario-based planning for partially dynamic vehicle routing with stochastic customers. *Operations Research*, 52:977–987, 2004.
8. E.K. Bish. A multiple-crane-constrained scheduling problem in a container terminal. *European Journal of Operational Research*, 144:83–107, 2003.
9. E.K. Bish, F.Y. Chen, Y.T. Leong, B.L. Nelson, J.W.C. Ng, and D. Simchi-Levi. Dispatching vehicles in a mega container terminal. *OR Spectrum*, 27:491–506, 2005.
10. E.K. Bish, T.-Y. Leong, C.-L. Li, J.W.C. Ng, and D. Simchi-Levi. Analysis of a new vehicle scheduling and location problem. *Naval Research Logistics*, 48:363–385, 2001.
11. L. Bodin, B. Golden, A. Assad, and M. Ball. Routing and scheduling of vehicles and crews : the state of the art. *Computers & Operations Research*, 10:63–211, 1983.
12. J. Böse, T. Reiners, D. Steenken, and S. Voß. Vehicle dispatching at seaport container terminals using evolutionary algorithms. In R.H. Sprague, ed., *Proc. of the 33rd Annual Hawaii Intern. Conf. on System Sciences (HICSS)*, vol 2. IEEE Computer Society, Los Alamitos, CA, USA, 2000.
13. O. Bräysy and M. Gendreau. Vehicle routing problem with time windows, part I: route construction and local search algorithms. *Transportation Science*, 39:104–118, 2005.
14. O. Bräysy and M. Gendreau. Vehicle routing problem with time windows, part II: metaheuristics. *Transportation Science*, 39:119–139, 2005.
15. D. Briskorn, A. Drexl, and S. Hartmann. Inventory-based dispatching of automated guided vehicles on container terminals. *OR Spectrum*, 28:611–630, 2006.

16. D. Briskorn and S. Hartmann. Simulating dispatching strategies for automated container terminals. In *Operations Research Proceedings 2005*, 97–102. Springer, Berlin, 2006.
17. G.G. Brown, K.J. Cormican, S. Lawphongpanich, and D.B. Widdis. Optimizing submarine berthing with a persistence incentive. *Naval Research Logistics*, 44:301–318, 1997.
18. A. Bruzzone and R. Signorile. Simulation and genetic algorithms for ship planning and shipyard layout. *Simulation*, 71:74–83, 1998.
19. H. Chang, H. Jula, A. Chassiakos, and P. Ioannou. Empty container reuse in the los angeles/long beach port area, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/Jula.pdf – last check of URL: April 19, 2007.
20. I.M. Chao. A tabu search method for the truck and trailer routing problem. *Computers & Operations Research*, 29:33–51, 2002.
21. L. Chen, N. Bostel, P. Dejax, J. Cai, and L. Xi. A tabu search algorithm for the integrated scheduling problem of container handling systems in a maritime terminal. *European Journal of Operational Research*, 181:40–58, 2007.
22. S.T. Choong, M.H. Cole, and E. Kutanoglu. Empty container management for intermodal transportation networks. *Transportation Research-E*, 38:423–438, 2002.
23. M. Christiansen, K. Fagerholt, B. Nygreen, and D. Ronen. Maritime transportation. In C. Barnhart and G. Laporte, eds., *Transportation. Handbooks in Operations Research and Management Science*, 189–284. Elsevier, Amsterdam, 2007.
24. M. Christiansen, K. Fagerholt, and D. Ronen. Ship routing and scheduling: Status and perspectives. *Transportation Science*, 38:1–18, 2004.
25. M. Christiansen and B. Nygreen. Robust inventory ship routing by column generation. In G. Desaulniers, J. Desrosiers, and M.M. Solomon, eds., *Column Generation*, 197–224. Springer (US), 2005.
26. N. Christofides, A. Mingozzi, and P. Toth. The vehicle routing problem. In N. Christofides, A. Mingozzi, P. Toth, and C. Sandi, eds., *Combinatorial optimization*, 315–338. Wiley, Chichester, UK, 1979.
27. J.-F. Cordeau, G. Laporte, P. Legato, and L. Moccia. Models and tabu search heuristics for the berth-allocation problem. *Transportation Science*, 39:526–538, 2005.
28. J.-F. Cordeau, G. Laporte, M.W.P. Savelsbergh, and D. Vigo. Vehicle routing. In C. Barnhart and G. Laporte, eds., *Transportation. Handbooks in Operations Research and Management Science*, vol 14, 367–428. Elsevier, Amsterdam, 2007.
29. L. Coslovich, R. Pesenti, and W. Ukovich. Minimizing fleet operating costs for a container transportation company. *European Journal of Operational Research*, 171:776–786, 2006.
30. T.G. Crainic and K.H. Kim. Intermodal transportation. In C. Barnhart and G. Laporte, eds., *Transportation. Handbooks in Operations Research and Management Science*, 467–537. Elsevier, Amsterdam, 2007.
31. S.K. Das and L.N. Spasovic. Scheduling material handling vehicles in a container terminal. *Production Planning & Control*, 14:623–633, 2003.
32. M. Desrochers, J.K. Lenstra, and M.W.P. Savelsbergh. A classification scheme for vehicle routing and scheduling problems. *European Journal of Operational Research*, 46:322–332, 1990.

33. B. Dimitrijevic and L.N. Spasovic. Innovative transportation technologies – an alternative for providing linkages between port terminals and inland freight distribution facilities, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/Dimitrijevic.pdf – last check of URL: April 19, 2007.
34. M. Dror, ed. *Arc Routing.* Kluwer, Boston, 2000.
35. M.B. Duinkerken, R. Dekker, S.T. Kurstjens, J.A. Ottjes, and N.P. Dellaert. Comparing transportation systems for inter-terminal transport at the Maasvlakte container terminals. *OR Spectrum*, 28:469–493, 2006.
36. M.B. Duinkerken, J.A. Ottjes, and G. Lodewijks. Comparison of routing strategies for AGV systems using simulation. In L.F. Perrone, F.P. Wieland, J. Liu, B.G. Lawson, D.M. Nicol, and R.M. Fujimoto, eds., *Proc. of the 2006 Winter Simulation Conf. (WSC 2006), Monterey, CA, USA, Dec 03–06*, 1523–1530. ACM, 2006.
37. R. Eisenberg, R. Stahlbock, S. Voß, and D. Steenken. Sequencing and scheduling of movements in an automated container yard using double rail-mounted gantry cranes. Working paper, University of Hamburg, 2003.
38. K. Fagerholt and M. Christiansen. A travelling salesman problem with allocation, time window and precedence constraints – an application to ship scheduling. *International Transactions in Operational Research*, 7:231–244, 2000.
39. T. Franz, S. Voß, and H. Rölke. Market-mechanisms for integrated container terminal management. In V. Bertram, ed., *Proc. of the 6th Intern. Conf. on Computer and IT Applications in the Maritime Industries, COMPIT'07, Cortona, Italy, April 23-25*, 234–248. INSEAN, 2007.
40. L.M. Gambardella, A.E. Rizzoli, and M. Zaffalon. Simulation and planning of an intermodal container terminal. *Simulation*, 71:107–116, 1998.
41. J.C. Gerdessen. Vehicle routing problem with trailers. *European Journal of Operational Research*, 93:135–147, 1996.
42. M. Goetschalckx and H.D. Ratliff. Order picking in an aisle. *IIE Transactions*, 20:53–62, 1988.
43. A.V. Goodchild. Crane double cycling in container ports: Algorithms, evaluation, and planning, 2005. PhD thesis, University of California at Berkeley, Department of Civil and Environmental Engineering.
44. A.V. Goodchild. Crane double cycling in container ports: planning methods and evaluation, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/Goodchild.pdf – last check of URL: April 19, 2007.
45. A.V. Goodchild. Port planning for double cycling crane operations, 2006. Paper presented at the TRB 2006 Annual Meeting, Washington, D.C., Jan 22-26.
46. A.V. Goodchild and C.F. Daganzo. Reducing ship turn-around time using double cycling. Technical report, University of California, Berkeley, Institute of Transportation Studies. Research Report UCB-ITS-RR-2004-4 (May 1), 2004.
47. A.V. Goodchild and C.F. Daganzo. Crane double cycling in container ports: Effect on ship dwell time. Technical report, University of California, Berkeley, Institute of Transportation Studies. Research Report UCB-ITS-RR-2005-5 (July), 2005.
48. A.V. Goodchild and C.F. Daganzo. Double-cycling strategies for container ships and their effect on ship loading and unloading operations. *Transportation Science*, 40:473–483, 2006.

49. M. Grunow, H.-O. Günther, and M. Lehmann. Dispatching multi-load AGVs in highly automated seaport container terminals. *OR Spectrum*, 26:211–235, 2004.
50. M. Grunow, H.-O. Günther, and M. Lehmann. Online- versus Offline-Einsatzplanung von Fahrerlosen Transportsystemen in Containerhäfen. In T. Spengler, S. Voß, and H. Kopfer, eds., *Logistik Management*, 399–410. Springer, Berlin, 2004.
51. M. Grunow, H.-O. Günther, and M. Lehmann. Strategies for dispatching AGVs at automated seaport container terminals. *OR Spectrum*, 28:587–610, 2006.
52. H. Gunnarsson, M. Rönnqvist, and D. Carlsson. A combined terminal location and ship routing problem. *Journal of the Operational Research Society*, 57:928–938, 2006.
53. H.-O. Günther and K.-H. Kim. Container terminals and terminal operations. *OR Spectrum*, 28:437–445, 2006.
54. G. Gutin and A.P. Punnen, eds. *The Traveling Salesman Problem and Its Variations*. Kluwer, Boston, 2002.
55. R.W. Hall. Distance approximations for routing manual pickers in a warehouse. *IIE Transactions*, 25:76–87, 1993.
56. I.A. Hansen. Automated shunting of rail container wagons in ports and terminal areas. *Transportation Planning and Technology*, 27:385–401, 2004.
57. R.F. Hartl, G. Hasle, and G.K. Janssens. Special issue on rich vehicle routing problem – editorial. *Central European Journal of Operations Research*, 14:103–104, 2006.
58. S. Hartmann. Generating scenarios for simulation and optimization of container terminal logistics. *OR Spectrum*, 26:171–192, 2004.
59. G. Hasle. Heuristics for rich VRP models. Presentation at ROUTE2003, Skodsborg, Denmark, June 24, 2003. http://www1.ctt.dtu.dk/ROUTE2003/presentations/Geir%20Hasle.ppt – last check of URL: Jan 14, 2007.
60. L.E. Henesey. *Enhancing Container Terminal Performance: A Multi Agent Systems Approach*. Blekinge Institute of Technology, Karlshamn (Sweden), 2004.
61. Y.C. Ho and S.H. Chien. A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs. *International Journal of Production Research*, 44:4193–4222, 2006.
62. Y.-C. Ho and P.-F. Hsieh. A machine-to-loop assignment and layout design methodology for tandem AGV systems with multiple-load vehicles. *International Journal of Production Research*, 42:801–832, 2004.
63. L. Hoffarth and S. Voß. Liegeplatzdisposition auf einem Containerterminal – Ansätze zur Entwicklung eines entscheidungsunterstützenden Systems. In H. Dyckhoff, U. Derigs, M. Salomon, and H. Tijms, eds., *Operations Research Proceedings 1993*, 89–95. Springer, Berlin, 1994.
64. C.-I. Hsu and Y.-P. Hsieh. Routing, ship size, and sailing frequency decision-making for a maritime hub-and-spoke container network. *Mathematical and Computer Modelling*, 45:899–916, 2007.
65. L.A.R. Hulten. *Container Logistics and its Management*. PhD thesis, Chalmers University of Technology: Department of Transportation and Logistics, 1997.
66. A. Imai, E. Nishimura, and J. Current. A lagrangian relaxation-based heuristic for the vehicle routing with full container load. *European Journal of Operational Research*, 176:87–105, 2007.

67. A. Imai, E. Nishimura, M. Hattori, and S. Papadimitriou. Berth allocation at indented berths for mega-containerships. *European Journal of Operational Research*, 179:579–593, 2007.
68. A. Imai, E. Nishimura, and S. Papadimitriou. The dynamic berth allocation problem for a container port. *Transportation Research-B*, 35:401–417, 2001.
69. A. Imai, E. Nishimura, and S. Papadimitriou. Berth allocation with service priority. *Transportation Research-B*, 37:437–457, 2003.
70. A. Imai, E. Nishimura, and S. Papadimitriou. Corrigendum to 'the dynamic berth allocation problem for a container port' [Transportation Research-B 35 (2001) 401–417]. *Transportation Research-B*, 39:197, 2005.
71. A. Imai, E. Nishimura, and S. Papadimitriou. Berthing ships at a multi-user container terminal with a limited quay capacity. *Transportation Research-E. In press, doi:10.1016/j.tre.2006.05.002*, online 2006.
72. A. Imai, E. Nishimura, S. Papadimitriou, and M. Liu. The economic viability of container mega-ships. *Transportation Research-E*, 42:21–41, 2006.
73. P. Ioannou, A. Chassiakos, J. Zhang, A. Kanaris, and R. Unglaub. Automated container transport system between inland port and terminals. Project Report, University of Southern California, 2002. http://www.usc.edu/dept/ee/catt/2003/jianlong/02%20METRANS%20Final %20Report.pdf – last check of URL: Jan 08, 2007.
74. P.A. Ioannou, E.B. Kosmatopoulos, H. Jula, A. Collinge, C.-I. Liu, A. Asef-Vaziri, and E. Dougherty Jr. Cargo handling technologies. Final Report, University of Southern California, 2000. http://www.usc.edu/dept/ee/catt/2002/jula/Marine/FinalReport_CCDoTT_97.pdf – last check of URL: Jan 08, 2007.
75. K.A. James and S. Gurol. Urban maglev freight container movement at the ports of Los Angeles/Long Beach, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/KenJames.pdf – last check of URL: April 19, 2007.
76. H. Jula, A. Chassiakos, and P. Ioannou. Port dynamic empty container reuse. *Transportation Research-E*, 42:43–60, 2006.
77. H. Jula, M. Dessouky, P. Ioannou, and A. Chassiakos. Container movement by trucks in metropolitan networks: modeling and optimization. *Transportation Research-E*, 41:235–259, 2005.
78. K.H. Kim and J.W. Bae. A dispatching method for automated guided vehicles to minimize delay of containership operations. *International Journal of Management Science*, 5:1–25, 1999.
79. K.H. Kim and J.W. Bae. A look-ahead dispatching method for automated guided vehicles in automated port container terminals. *Transportation Science*, 38:224–234, 2004.
80. K.H. Kim, S.M. Jeon, and K.R. Ryu. Deadlock prevention for automated guided vehicles in automated container terminals. *OR Spectrum*, 28:659–679, 2006.
81. K.H. Kim and K.Y. Kim. An optimal routing algorithm for a transfer crane in port container terminals. *Transportation Science*, 33:17–33, 1999.
82. K.H. Kim and K.Y. Kim. Routing straddle carriers for the loading operation of containers using a beam search algorithm. *Computers & Industrial Engineering*, 36:106–136, 1999.

83. K.H. Kim and Y.-M. Park. A crane scheduling method for port container terminals. *European Journal of Operational Research*, 156:752–768, 2004.
84. K.H. Kim, S.J. Wang, Y.-M. Park, C.-H. Yang, and J.W. Bae. A simulation study on operation rules for automated container yards. In *Proc. of the 7th Annual Intern. Conf. on Industrial Engineering, Pusan, Korea*, 250–253, 2002.
85. K.Y. Kim and K.H. Kim. A routing algorithm for a single transfer crane to load export containers onto a containership. *Computers & Industrial Engineering*, 33:673–676, 1997.
86. K.Y. Kim and K.H. Kim. A routing algorithm for a single straddle carrier to load export containers onto a containership. *International Journal of Production Economics*, 59:425–433, 1999.
87. K.Y. Kim and K.H. Kim. Heuristic algorithms for routing yard-side equipment for minimizing loading times in container terminals. *Naval Research Logistics*, 50:498–514, 2003.
88. P.-H. Koo, W.S. Lee, and D.W. Jang. Fleet sizing and vehicle routing for container transportation in a static environment. *OR Spectrum*, 26(2):193–209, 2004.
89. E.L. Lawler, J.K. Lenstra, A.H.G. Rinnooy Kan, and D.B. Shmoys, eds. *The Traveling Salesman Problem – A Guided Tour of Combinatorial Optimization*. Wiley, Chichester, 1985.
90. D.-H. Lee, Z. Cao, and Q. Meng. Scheduling of two-transtainer systems for loading outbound containers in port container terminals with simulated annealing algorithm. *International Journal of Production Economics*, 107:115–124, 2007.
91. D.-H. Lee, H.Q. Wang, and L. Miao. Quay crane scheduling with non-interference constraints in port container terminals. *Transportation Research-E. In press, doi:10.1016/j.tre.2006.08.001*, online 2006.
92. J. Lee and T. Srisawat. Effect of manufacturing system constructs on pick-up and drop-off strategies of multiple-load AGVs. *International Journal of Production Research*, 44:653–673, 2006.
93. M. Lehmann, M. Grunow, and H.-O. Günther. Deadlock handling for real-time control of AGVs at automated container terminals. *OR Spectrum*, 28:631–657, 2006.
94. B. Lemper. Containerschifffahrt und Welthandel – eine 'Symbiose', Mar 2003. http://www.hansika-gmbh.de/PDF/Containerschifffahrt_und_Welthandel.pdf – last check of URL: Jan 11, 2007.
95. J.-A. Li, S.C.H. Leung, Y. Wu, and K. Liu. Allocation of empty containers between multi-ports. *European Journal of Operational Research. In press, doi:10.1016/j.ejor.2006.09.003*, online 2006.
96. J.-A. Li, K. Liu, S.C.H. Leung, and K.K. Lai. Empty container management in a port with long-run average criterion. *Mathematical and Computer Modelling*, 40:85–100, 2004.
97. A. Lim, B. Rodrigues, F. Xiao, and Y. Zhu. Crane scheduling with spatial constraints. *Naval Research Logistics*, 51:386–406, 2004.
98. A. Lim, B. Rodrigues, and Z. Xu. Approximation schemes for the crane scheduling problem. In *Algorithm Theory – SWAT 2004: 9th Scandinavian Workshop on Algorithm Theory, Humlebaek, Denmark, July 8–10*, 323–335. Springer, Berlin, 2004.

99. A. Lim, B. Rodrigues, and Z. Xu. Solving the crane scheduling problem using intelligent search schemes (extended abstract). In M. Wallace, ed., *Principles and Practice of Constraint Programming — Proc. of 10th Intern. Conf. CP 2004, Toronto, Canada, Sep 27–Oct 1*, 747–751. Springer, Berlin, 2004.
100. A. Lim, B. Rodrigues, and Z. Xu. A m-parallel crane scheduling problem with a non-crossing constraint. *Naval Research Logistics*, 54:115–127, 2007.
101. C.-I. Liu, H. Jula, and P.A. Ioannou. Design, simulation, and evaluation of automated container terminals. *IEEE Transactions on Intelligent Transportation Systems*, 3:12–26, 2002.
102. D. Martinssen, D. Steenken, F. Wölfer, T. Reiners, and S. Voß. Einsatz bioanaloger Verfahren bei der Optimierung des wasserseitigen Containerumschlags. In H. Sebastian and T. Grünert, eds., *Logistik Management – Supply Chain Management und e-Business*, 377–388. Teubner, Stuttgart, 2001.
103. P.J.M. Meersmans and A.P.M. Wagelmans. Effective algorithms for integrated scheduling of handling equipment at automated container terminals. Technical Report EI 2001-19, Erasmus University Rotterdam – Econometric Institute, June 2001. http://www.eur.nl/WebDOC/doc/econometrie/feweco20010621101333.pdf – last check of URL: Jan 08, 2007.
104. L. Moccia, J.-F. Cordeau, M. Gaudioso, and G. Laporte. A branch-and-cut algorithm for the quay crane scheduling problem in a container terminal. *Naval Research Logistics*, 53:45–59, 2006.
105. R.H. Möhring, E. Köhler, E. Gawrilow, and B. Stenzel. Conflict-free real-time AGV routing. In H. Fleuren, D. den Hertog, and P. Kort, eds., *Operations Research Proceedings 2004*, 18–24. Springer, Berlin, 2005.
106. G. Muller. *Intermodal Freight Transportation*. Eno Foundation for Transportation, Westport, CN, 1995.
107. K.G. Murty, J. Liu, Y.-w. Wan, and R. Linn. A decision support system for operations in a container terminal. *Decision Support Systems*, 39:309–332, 2005.
108. R. Namboothiri and A.L. Erere. A column generation heuristic for local drayage routing given a port access appointment system, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/erera_nambo.pdf – last check of URL: April 19, 2007.
109. W.C. Ng. Crane scheduling in container yards with inter-crane interference. *European Journal of Operational Research*, 164:64–78, 2005.
110. W.C. Ng and K.L. Mak. Sequencing of container pickup trucks in container yard blocks. *International Journal of Industrial Engineering*, 11:82–89, 2004.
111. W.C. Ng and K.L. Mak. An effective heuristic for scheduling a yard crane to handle jobs with different ready times. *Engineering Optimization*, 37:867–877, 2005.
112. W.C. Ng and K.L. Mak. Yard crane scheduling in port container terminals. *Applied mathematical modelling*, 29:263–276, 2005.
113. W.C. Ng and K.L. Mak. Quay crane scheduling in container terminals. *Engineering Optimization*, 38:723–737, 2006.
114. W.C. Ng, K.L. Mak, and Y.X. Zhang. Scheduling trucks in container terminals using a genetic algorithm. *Engineering Optimization*, 39:33–47, 2007.

115. V.D. Nguyen and K.H. Kim. A dispatching method for automated lifting vehicles in automated port container terminals, 2007. Paper presented at the Intern. Conf. on Intelligent Manufacturing & Logistics Systems (IML 2007), Kitakyushu, Japan, Feb 26–28.
116. E. Nishimura, A. Imai, and S. Papadimitriou. Yard trailer routing at a maritime container terminal. *Transportation Research-E*, 41:53–76, 2005.
117. NKM Noell Special Cranes GmbH & Co KG. Crane construction. http://www.nkmnoell.com/ – last check of URL: Jan 04, 2007, Sep 2003.
118. J.A. Ottjes, H.P.M. Veeke, M.B. Duinkerken, J.C. Rijsenbrij, and G. Lodewijks. Simulation of a multiterminal system for container handling. *OR Spectrum*, 28:447–468, 2006.
119. Y.-M. Park and K.H. Kim. A scheduling method for berth and quay cranes. *OR Spectrum*, 25:1–23, 2003.
120. R.I. Peterkofsky and C.F. Daganzo. A branch and bound solution method for the crane scheduling problem. *Transportation Research-B*, 24B:159–172, 1990.
121. L. Qiu, W.-J. Hsu, S.Y. Huang, and H. Wang. Scheduling and routing algorithms for AGVs: A survey. *International Journal of Production Research*, 40:745–760, 2002.
122. H.D. Ratliff and A.S. Rosenthal. Order-picking in a rectangular warehouse: A solvable case of the traveling salesman problem. *Operations Research*, 31:507–521, 1983.
123. L. Rohter, C. Jackson, B. Dahnke, A. Iris, and G. Rawling. Automated shipping container transportation system design for Chicago, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/dahnke.pdf – last check of URL: April 19, 2007.
124. S. Roop. The freight shuttle: The crisis in freight transportation and the opportunity for a green alternative, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/Roop.pdf – last check of URL: April 19, 2007.
125. Y. Saanen, J. van Meel, and A. Verbraeck. The next generation automated container terminals. Technical report, TBA Nederland/Delft University of Technology, 2003.
126. Y.A. Saanen and M.V. Valkengoed. Comparison of three automated stacking alternatives by means of simulation. In M.E. Kuhl, N.M. Steiger, F.B. Armstrong, and J.A. Joines, eds., *Proc. of the 2005 Winter Simulation Conf. (WSC 2005), Orlando, FL, USA, Dec 4–7*, 1567–1576. ACM, 2005.
127. S. Scheuerer. A tabu search heuristic for the truck and trailer routing problem. *Computers & Operations Research*, 33:894–909, 2006.
128. G. Schneidereit, S. Voß, A. Parra, and D. Steenken. A general pickup and delivery problem for automated guided vehicles with multiloads: A case study. Working paper, University of Hamburg, 2003.
129. F. Semet. A two-phase algorithm for the partial accessibility constrained vehicle routing problem. *Annals of Operations Research*, 61:45–65, 1995.
130. X.N. Shi and S. Voß. Container terminal operations under the influence of shipping alliances. Working paper, University of Hamburg, 2007.
131. K. Shintani, A. Imai, E. Nishimura, and S. Papadimitriou. The container shipping network design problem with empty container repositioning. *Transportation Research-E*, 43:39–59, 2007.

132. D.P. Song. Characterizing optimal empty container reposition policy in periodic-review shuttle service systems. *Journal of the Operational Research Society*, 58:122–133, 2006.
133. D. Steenken. Fahrwegoptimierung am Containerterminal unter Echtzeitbedingungen. *OR Spektrum*, 14:161–168, 1992.
134. D. Steenken. Optimised vehicle routing at a seaport container terminal. *ORbit*, 4:8–14, 2003.
135. D. Steenken, A. Henning, S. Freigang, and S. Voß. Routing of straddle carriers at a container terminal with the special aspect of internal moves. *OR Spektrum*, 15:167–172, 1993.
136. D. Steenken, S. Voß, and R. Stahlbock. Container terminal operations and operations research – a classification and literature review. *OR Spectrum*, 26:3–49, 2004.
137. M. Taleb-Ibrahimi, B. de Castilho, and C.F. Daganzo. Storage space vs handling work in container terminals. *Transportation Research-B*, 27:13–32, 1993.
138. K.C. Tan, Y.H. Chew, and L.H. Lee. A hybrid multi-objective evolutionary algorithm for solving truck and trailer vehicle routing problems. *European Journal of Operational Research*, 172:855–885, 2006.
139. T. Thurston and H. Hu. Distributed agent architecture for port automation. In *Proc. of the 26th Annual Intern. Computer Software and Applications Conf. (COMPSAC'02), Oxford, UK, Aug 26–29*, 81–87. IEEE Computer Society, Los Alamitos, CA, USA, 2002.
140. P. Toth and D. Vigo, eds. *The Vehicle Routing Problem*. Society for Industrial & Applied Mathematics, SIAM, Philadelphia, 2002.
141. United Nations Conference on Trade and Development – secretariat. Review of maritime transport, Dec 2006. http://www.unctad.org/en/docs/rmt2006_en.pdf – last check of URL: Jan 8, 2007.
142. R. van der Meer. *Operational Control of Internal Transport*. Phd, Erasmus University, Rotterdam, The Netherlands, 2000.
143. A.W. Veenstra, N. Lang, and B. van den Rakt. Economic analysis of a container terminal simulation. *International Journal of Logistics*, 7:263–279, 2004.
144. M. Vidovic, T. Baltacioglu, Ö. Yurt, and G. Özkan. Matching algorithms for the vehicle routing in containers delivery and collecting problems. In *Proc. of The 7th Balkan Conf. on Operational Research (BACOR 05), Constanta, Romania, May 25–28*, 2005. http://fmi.unibuc.ro/balkan-conf/CD/Section4/Vidovic.pdf – last check of URL: Jan 14, 2007.
145. I.F.A. Vis. A comparative analysis of storage and retrieval equipment at a container terminal. *International Journal of Production Economics*, 103:680–693, 2006.
146. I.F.A. Vis. Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research*, 170:677–709, 2006.
147. I.F.A. Vis and R. de Koster. Transshipment of containers at a container terminal: An overview. *European Journal of Operational Research*, 147:1–16, 2003.
148. I.F.A. Vis, R. de Koster, K.J. Roodbergen, and L.W.P. Peeters. Determination of the number of automated guided vehicles required at a semi-automated container terminal. *Journal of the Operational Research Society*, 52:409–417, 2001.

149. I.F.A. Vis and I. Harika. Comparison of vehicle types at an automated container terminal. *OR Spectrum*, 26:117–143, 2004.
150. B. Volk. Growth factors in container shipping, Apr 2002. http://maritimebusiness.amc.edu.au/papers/AMC3_GRO.pdf – last check of URL: Jan 8, 2007.
151. S. Voß and J.W. Böse. Innovationsentscheidungen bei logistischen Dienstleistern – Praktische Erfahrungen in der Seeverkehrswirtschaft. In W. Dangelmaier and W. Felser, eds., *Das reagible Unternehmen*, 253–282. HNI, Paderborn, 2000.
152. S. Voß and J.R. Daduna, eds. *Computer-Aided Scheduling of Public Transport*. Springer, Berlin, 2001.
153. J.C.F. Wong and J.M.Y. Leung. On a vehicle routing problem with time windows and stochastic travel times. Technical report, Department of Systems Engineering and Engineering Management, Chinese University of Hong Kong, China, 2002.
154. H. Zhang and K.H. Kim. Dual cycling quay crane optimization with constraints of twin lift, 2007. Paper presented at the Intern. Conf. on Intelligent Manufacturing & Logistics Systems (IML 2007), Kitakyushu, Japan, Feb 26–28.
155. J. Zhang, P.A. Ioannou, and A. Chassiakos. Intelligent transportation system for container movement between inland port and terminals, 2006. Paper presented at the METRANS National Urban Freight Conf., Feb. 1-3, Long Beach, CA, USA. http://www.metrans.org/nuf/documents/Zhang.pdf – last check of URL: April 19, 2007.
156. Y. Zhu and A. Lim. Crane scheduling with spatial constraints: Mathematical model and solving approaches. In *AI&M 30-2004, Eighth Intern. Symposium on Artificial Intelligence and Mathematics, Fort Lauderdale, FL, USA, Jan 4–6*, 2004.
157. Y. Zhu and A. Lim. Crane scheduling with non-crossing constraint. *Journal of the Operational Research Society*, 57:1464–1471, 2006.