Sea Container Terminals: New Technologies, OR models, and Emerging Research Areas

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Abstract

Due to a rapid growth in world trade and a huge increase in containerized goods, sea container terminals play a vital role in globe-spanning supply chains. Container terminals should be able to handle large ships, with large call sizes within the shortest time possible, and at competitive rates. In response, terminal operators, shipping liners, and port authorities are investing in new technologies to improve container handling infrastructure and operational efficiency. Container terminals face challenging research problems which have received much attention from the academic community. **The focus of this paper is to highlight the recent developments in the container terminals, which can be categorized into three areas: (1) innovative container terminal technologies, (2) new OR directions and models for existing research areas, and (3) emerging areas in container terminal research. By choosing this focus, we complement existing reviews on container terminal operations.**
KEYWORDS: Container terminal; literature review; optimization; heuristic; simulation

1 Introduction

Since the introduction of the container in April 1956, when Malcolm McLean moved fifty-eight 35 foot containers from Newark to Houston by a refitted oil tanker, container flows have increased continuously. Annually, about 108 million cargo containers are transported through seaports around the world, constituting the most critical component of global trade. Between 1990 and 2015, the total number of full containers shipped internationally is expected to grow from 28.7 million to 177.6 million (United Nations: ESCAP, 2007). A simple calculation shows that there are enough containers on the planet to build more than two 8-foot-high walls around the equator (Taggart, 1999).

Containerization has become the main driver for intermodal freight transport, which involves the transportation of freight in containers of standard dimensions (20 ft equivalent unit (1 TEU), 40 ft (2 TEU), 45 ft (high-cube)), using multiple modes of transportation such as ships, trucks, trains, or barges without any handling of the freight itself when changing modes (Crainic and Kim, 2007). Bundling freight in containers reduces cargo handling, and thereby improves security, reduces damages and losses, and allows freight to be transported faster (Agerschou et al., 1983). In the chain of intercontinental transport, container terminals are of special importance since all containers pass through at least one of them during their drayage. Container terminals are the nodes where different modalities meet to transport containers.

Container terminals have received increasing attention from the academic community due to the opportunities and challenges they offer in research. Multiple reviews have been published in the last decade, focusing on the use of operations research models for handling containers (Vis and De Koster, 2003; Steenken et al., 2004a; Günther and Kim, 2005; Murty et al., 2005; Stahlbock and

Voß, 2008a; Gorman et al., 2014). **Parallel to this paper, three focused reviews, focusing on seaside, transport, and and stackside storage operations have appeared (Carlo et al., 2014b, 2013, 2014a). However, this paper provides an integrated view of the container terminal operations on recent literature. We specifically focus on the new technological developments, OR models, and new areas of research.** The scope of this study is restricted to internal operations at a container terminal.

We have searched for all papers published since 2008 in which both "container" and "terminal" appear in the abstract, and which use "operations", "handling", and "optimization" in the main text. We have searched the following large scientific databases: ABI/Inform Complete, Business Source Premier, JSTOR, Proquest Platform, Science Direct, and Web of Knowledge. We review papers that use OR models to make or evaluate decisions in container terminals. **From the resulting list of 177 papers, we have included all papers from journals that contribute to one of our focus areas.** We have complemented this list with other sources (including papers from all other journals, theses, working papers, and internet sources) if they are of added value to the topic under discussion. In each section, we try to achieve a comprehensive list of citations. In total, we cite 216 sources, of which 144 have appeared since 2008.

1.1 Container terminal operations

Container handling equipment includes quay cranes (QCs), yard cranes (YCs), automated guided vehicles (AGVs), and straddle carriers (SCs). These systems are shown in Figures 1a–d, and are used to transship containers from ships to barges, trucks and trains, and vice versa. Other new equipment is introduced in the next sections. Containers can be transshipped directly from one mode of transportation to another. Alternatively, containers can be stored for a certain period in a stack, before they are transferred to another mode. Material handling equipment used at a terminal is very expensive, regardless of whether it is automated or manned. The investment in a single modern container terminal can be as high as €1 billion or more and the payback period ranges between 15–30 years (Wiegmans et al., 2002; De Koster et al., 2009).

(a) QC (b) YC (c) AGV (d) SC

Figure 1: A top view of a container terminal and material handling equipment (Source: Europe Container Terminals (ECT), 2012)

Sea container terminals are divided into several areas such as seaside, landside, stacking, and internal transport areas that cater to seaside and landside operations (see Figure 2). At a container terminal, QCs load and unload containers from ships berthed along the quay at the seaside. QCs pick up or drop off containers on AGVs which transport containers from the seaside to the stacking area where YCs take over. Finally, SCs transport containers either between the YCs and trucks or between the YCs and trains at the landside. In more traditional container terminals, SCs are also used to stack containers.

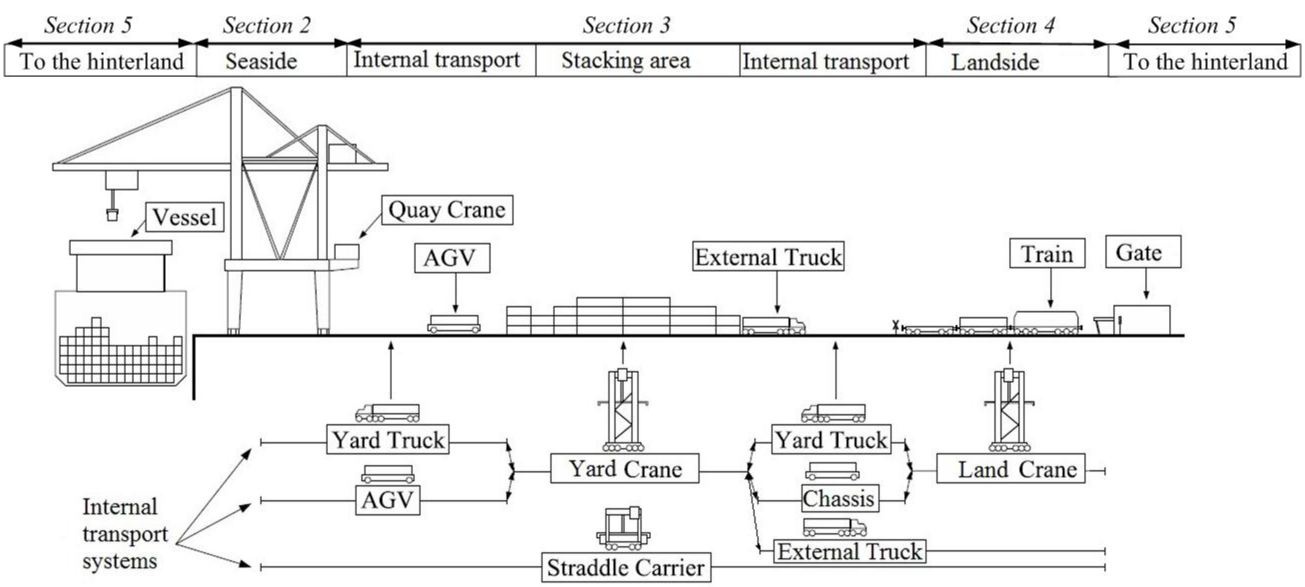
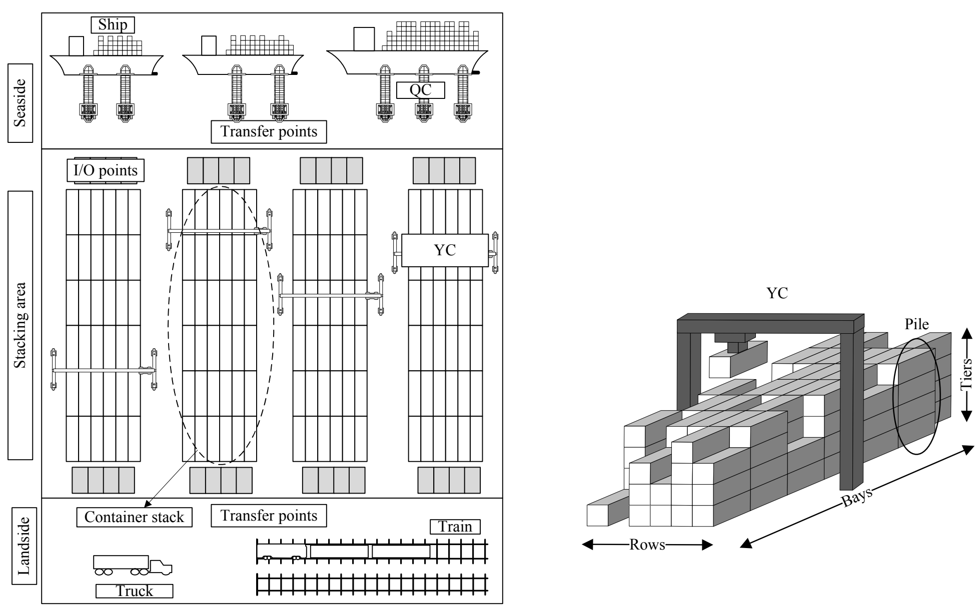


Figure 2: Loading and unloading processes of containers at a typical container terminal (adapted from Brinkmann, 2010 and Meisel, 2009)

At an automated container terminal, containers are stacked in container stacks. Figure 3a depicts a typical container terminal layout with several container stacks in the stack area; other terminal layouts are studied by Wiese et al. (2010). Each stack consists of multiple rows, tiers, and bays as shown in Figure 3b. Containers arrive or leave the terminal at the seaside or landside and spend a period of time in these stacks. Input/output (I/O) points are located at each stack end and a single YC is used to stack and retrieve containers in that stack. A container's storage position within container stacks is mainly determined by the loading sequence onto the ships. This sequence depends on the container's ship departure time, its port of destination, and its weight. Obviously, containers have to be retrieved from the stack in the sequence of the departure of their corresponding ships. Furthermore, containers have to be loaded onto the ship in a reverse order of the sequence of destination. Containers with a later destination have to be loaded first. Finally, containers have to be loaded according to their weight. In order to ensure a ship's stability, heavier containers should be loaded before lighter ones. Many other practical constraints are considered while loading a ship (i.e., dynamic stability, container sizes, containers with hazardous materials, reefer containers, etcetera). However, some flexibility may be permitted while retrieving containers from the stack to load a ship, because multiple QCs load a ship in parallel, and vehicles can be assigned to retrieve containers in a particular sequence. In addition, stacks constantly change due to pre-marshalling.



(a) Top view of a container terminal (b) Container stack

Figure 3: Schematic representation of a container terminal layout

1.2 Latest trends in container terminals

A large terminal handles millions of containers annually (Drewry, 2011). Container terminals in the Port of Rotterdam handled more than 11 million TEU in 2011 while those in Shanghai handled more than 30 million TEU in the same year (Port of Rotterdam Authority, 2012). Because many containers have to be stacked temporarily, more land is needed for the related supply chain activities. Lack of space has driven container terminal operators to build higher container stacks. In addition, ships have grown larger over the past decades with larger loadings and unloadings at ports. The largest Post-Panamax ships can carry about 15,000 TEU, compared to the first generation ships, which had a capacity of about 400 TEU (Port of Rotterdam Authority, 2012)). Shipbuilding companies are planning for new ships of up to 18,000 or even 20,000 TEU. Large ships can only berth in ports with deep water, **at terminals with sufficiently wide gantry cranes, with adequate terminal material handling systems, and with adequate hinterland connections.** This limits the number of ports of call and increases the drop size per terminal visited. Thus, larger ships spend more time in port than smaller ships. For instance, an 8,000 TEU ship spends 24% of its overall voyage time in port compared to 17% for a 4,000 TEU Panamax ship (Midoro et al., 2005). An idle 2,000 TEU ship costs $20,000-$25,000 per day (Agarwal and Ergun, 2008). Container terminal managers are constantly looking for new technologies and methodologies to efficiently handle all the containers arriving and leaving terminals.

In recent years, port authorities and many companies in several countries have started to integrate supply chain and transportation activities by extending the sea terminal gate into the hinterland (Veenstra et al., 2012; Iannone, 2012). Previously, integrated hinterland terminals were introduced as “dry ports”. As Figure 4 shows different firms in multi-modal hinterland networks, such as terminal operators, freight forwarders, information service providers, infrastructure managers, shippers, and receivers play a role. All these firms aim to contribute to a better performance of the overall supply chain. Terminal operators, for instance, are more and more involved in linking sea terminals with inland terminals. It enables them to better connect with shippers and receivers in the network. This change comes with serious and unexplored challenges, but it also provides an opportunity to develop a sustainable and competitive advantage. The seamless flow of goods from seaports to locations far into the hinterland can prevent negative external effects from the transport, such as congestion in seaports, or on motorways due to too much trucking.

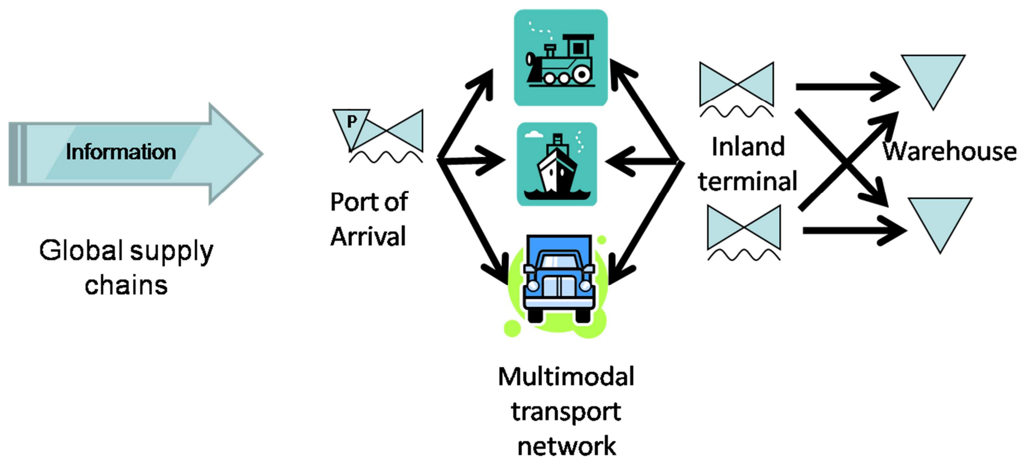


Figure 4: The supply chain of a container terminal (source: Veenstra et al., 2012)

Many other initiates have been started to efficiently mange container terminals. Faster, more automated, and more sustainable container handling equipment, able to handle large ships, has been designed. Different terminal layout designs have been considered. In summary, the developments covered in this paper are:

1. Higher degrees of automation: newer and faster equipment (larger and faster QCs, lifting vehicles, multiple cranes per stack),
2. Alternative layouts (YC stacking, stacks parallel or perpendicular to the quay, indented berths, higher stacks),
3. Increasing ship sizes and emphasis on reducing ship turnaround time,
4. Increased security requirements,
5. More sustainable container terminals, reducing energy consumption and CO2 emissions (green terminals).

In the subsequent sections of this paper, we briefly mention recent papers studying these topics using operations research tools. In addition, we try to identify new and important topics which are still pristine and offer a great opportunity for operational researchers. We start with seaside operations in Section 2, and then discuss internal transport and stack operations in Sections 3 and 4, respectively. Organizing and exposing container terminal operations in a "seaside-stacking area-landside" framework to review the relevant papers was initially suggested by Steenken et al. (2004b) and then followed by Stahlbock and Voß (2008a). We expand this framework to a "seaside-stacking area-landside-*hinterland*" framework. Nowadays, deep-sea terminals have become excessively busy. Due to lack of space, pollution, and long waiting times, integrated hinterland terminals have become an essential part of container terminals. Therefore, a survey on container terminal operations should include the recent developments and literature on hinterland operations. Section 5 is dedicated to discuss hinterland operations and the consequences for container terminals. **Each section, which is devoted to a specific container terminal process (seaside, transport, stacking area, and hinterland), is composed of two subsections. We first discuss the new technologies and then we describe the new developments in OR models. The emerging areas of research are summarized in Section 6. Section 7 concludes the paper.**

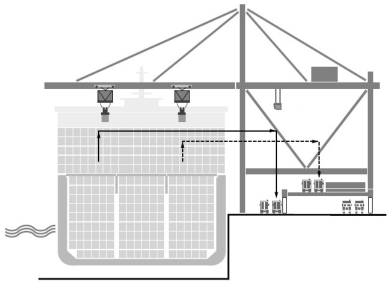
2 Seaside operations

Seaside operations planning consists of ship berthing operations (berth planning and quay crane scheduling), and loading and unloading of containers onto ships. Further, the stowage planning where the sequence of loading and unloading containers in a ship is optimized plays a critical role in the seaside operations planning. In this section, we discuss technological advancements in QCs and also review some of the recent work in this important area.

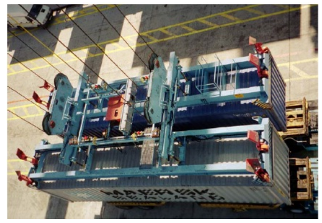
2.1 New technologies

Recently, a new generation of fully automated (remote controlled) QCs has been developed. As shown in Figure 5a-c, they are equipped with two trolleys, each capable of handling two or even three TEU at the same time. In some designs, QCs are equipped with shuttles on the boom to reduce the horizontal handling time, or with trolleys that can rotate 90 degrees, as respectively shown in Figures 5d-e. In Section 4, we discuss other designs in which QCs spread over an indented berth, or in which the QCs float on the water to build artificial temporary space.

Since the new designs can be used more flexibly with higher capacity compared to traditional QCs, the existing models may have to be adopted to these new developments. For example, Xing et al. (2011) analyze the problem of dispatching AGVs in container terminals equipped with tandem lift QCs that require two AGVs to be ready simultaneously to unload containers. The problem is formulated by a mixed-integer linear programming model and a decomposition method is used to solve the problem.

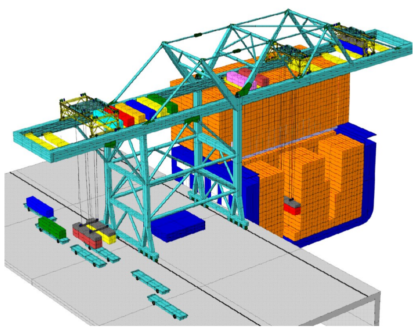


(a) Double trolley QC (Source: Jordan, 1997)

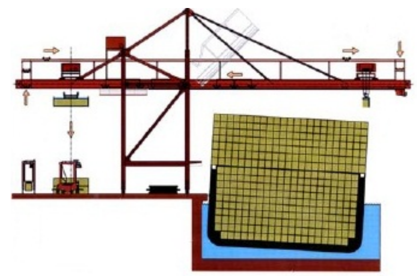


(b) QC with a double lifting trolley (Source: Jordan, 2002)

(c) QC with a triple lifting trolley (Source: China Communications construction company, 2010)



(d) QC with shuttles performing horizontal transport on the boom (Source: Giebel, 2003)



(e) QC with 90 degrees rotating trolleys (Source: Jordan, 2002)

Figure 5: New generation of QCs

2.2 OR models

Quay crane and berth operations planning

When a ship arrives, several tactical and operational decisions are made — such as allocating berthing space, berthing time, and assigning a set of QCs — to process container loading and unloading operations with minimum terminal cost and delays. The first problem is commonly known as the berth allocation problem (BAP). The optimal allocation of berths to incoming ships is very complex because of spatial constraints such as the draft requirement for ship berthing, ship size, space availability, and the distance between the berthing location to the stacks where ship's containers are stacked. The complexity of the problem is further increased due to temporal constraints (static vs. dynamic arrival of ships). The second problem is related to assigning QCs to the ship. Modeling challenges such as addressing the interference between QCs and improving crane productivity, makes this problem interesting from both a research and a practical viewpoint. The third problem is related to scheduling QCs to unload or load a group of containers from/to the ship by adhering to task precedence constraints. Until recently, the research community has mostly addressed the problems in isolation. However, due to interactions among the decisions, currently new algorithms and heuristic approaches have been developed to solve these problems within an integrated framework.

Figure 6 illustrates a berth plan with four ships. In Figure 6, the x and y axes denote the ship berthing time and the ship berthing space respectively. In Figure 6b, the QCs are assigned to each ship. Note that QC 2 is reassigned from ship 1 to ship 2, after its process is complete.

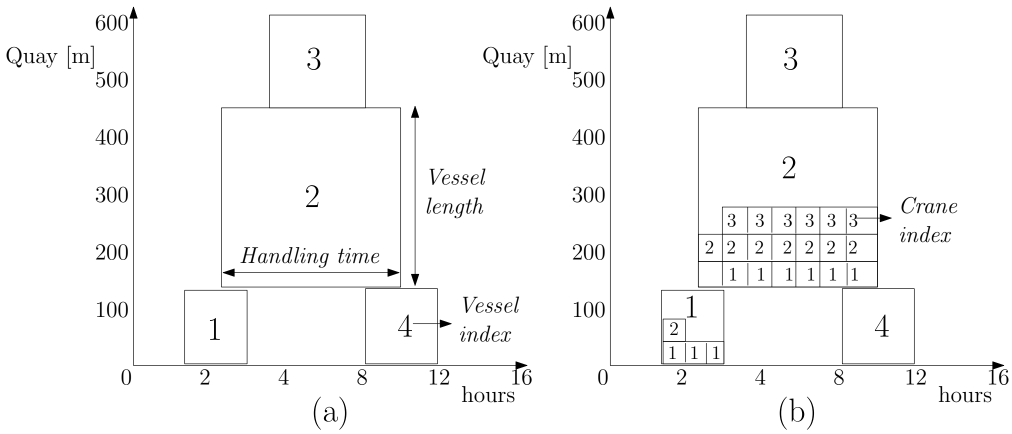


Figure 6: Illustration of (a) the berth allocation problem and (b) the QC assignment problem (adapted from Bierwirth and Meisel, 2010)

We now discuss these problems in more detail and review the recent OR modeling contributions. For a comprehensive survey on berth allocation and QC scheduling problems including papers prior to 2010, see Bierwirth and Meisel (2010).

Berth Allocation Problem (BAP): To minimize the sum of ship waiting and handling times (port stay times), optimization models have been developed by fixing the choice of spatial, temporal, and handling time attributes. For example, the spatial attribute denotes whether the quay area is partitioned into discrete or continuous berths (Buhrkal et al., 2011). The temporal attribute indicates the restriction imposed on the ship berthing time or departure time. Likewise, the handling time attribute indicates if the ship handling time is fixed or dependent on berthing position, QC assignment, or QC schedules. Hansen et al. (2008) solve the dynamic BAP problem by taking into account the service costs of ships depending on the berth they are assigned to in addition to the handling times. The continuous dynamic BAP with both fixed and berth-position dependent handling times has received considerable attention from researchers (Wang and Lim, 2007). many other version of the BAP has been considered by researchers. Hendriks et al. (2010) study a robust BAP in which cyclically calling ships have arrival time windows, instead of specific arrival times. They minimize the maximum amount of QC capacity required in different scenarios. In a later study, Hendriks et al. (2012) work on a similar problem in which cyclically calling ships have to be processed in different terminals of the same port. They minimize the amount of inter-terminal transport, and balance the QC workload in different terminals and time periods. Xu et al. (2012) study the BAP considering the water depth and tidal condition constraints. They model the problem in a static mode (all ships are available) and a dynamic mode (ships arrive over time). They develop efficient heuristics to solve the problems. Nowadays, environmental issues are also considered in BAP models. Du et al. (2011) propose an integer model which not only maintains the service level of the terminal but also considers fuel consumptions and vessel emissions.

QC Assignment Problem (QCAP): After allocating a berth space to a ship, a set of QCs are assigned to the ship such that the crane productivity is maximized by reducing the number of QC setups and QC travel times. The two problems, QCAP and BAP, are closely interrelated, since once the QCs are allocated, the ship handling times are affected. In practice, QCAP is solved using rules of thumb and has received little attention from researchers (Bierwirth and Meisel, 2010).

Giallombardo et al. (2010) propose two formulations for combining the BAP and QCAP: a mixed-integer quadratic program and a linearization which reduces to a mixed-integer linear program. To solve the problem, they develop a heuristic which combines tabu search methods and mathematical programming techniques. Han et al. (2010) consider a similar problem, but with stochastic ship arrival time and handling time. They formulate the problem as a mixed-integer programming model and solve it by a simulation-based Genetic Algorithm. Chang et al. (2010) study the problem in a rolling horizon fashion. They solve the model by a parallel genetic algorithm in combination with a heuristic algorithm.

Table 1 compares the existing models for the BAP (some integrated with the QCAP) based on the classification introduced by Bierwirth and Meisel (2010). Problems are classified according to *spatial* | *temporal* | *handling time* | *performance measure* attributes. A complete discussion on the classification scheme and associated abbreviations can be found in their survey.

Table 1: Overview of BAP formulations

Problem classification	Reference
Comparing discrete BAP models including the following two	Buhrkal et al. (2011)
$disc\|stat\|pos\| \sum(wait + hand)$	Imai et al. (2001)
$disc\|dyn, due\|pos\| \sum(wait + hand)$	Cordeau et al. (2005)
$disc\|dyn\|pos\| \sum(w_1 wait + w_2 tard + w_3 pos)$	Hansen et al. (2008)
$cont\|dyn, due\|QCAP\|max(res)$	Hendriks et al. (2010)
$cont\|dyn, due\|QCAP\| \sum(w_1 res + w_2 misc)$	Hendriks et al. (2012)
$disc, draft\|stat, dyn\|fix\| \sum(wait + hand)$	Xu et al. (2012)
$cont\|dyn\|fix\| \sum(w_1 tard + w_2 speed)$, extending the following one	Du et al. (2011)
$cont\|dyn\|fix\| \sum(w_1 tard + w_2 pos)$	Kim and Moon (2003) or Park and Kim (2003)
$disc, draft\|dyn, due\|pos\| \sum(w_1(wait + hand) + w_2 tard)$	Han et al. (2010)
$disc\|dyn, due\|QCAP\| - \sum(w_1 res - w_2 pos)$	Giallombardo et al. (2010)
$cont\|dyn, due\|QCAP\| \sum(w_1 pos + w_2 tard + w_3 misc)$	Chang et al. (2010)

Note. References are sorted in order of appearance in the text. Abbreviations used in the table are:

Spatial attribute: *disc*: discrete berth, *cont*: continuous berth, *draft*: draft of a ship.

Temporal attribute: *stat*: no restriction on berthing times, *dyn*: ships have different arrival times, *due*: ships have different departure times.

Handling time attribute: *pos*: handling times depend on berthing positions, *fix*: fixed handling times, *QCAP*: handling times depend on QC assignments.

Performance measure: *wait*: waiting time, *hand*: handling time, *tard*: tardiness, *res*: resource utilization, *misc*: miscellaneous.

QC Scheduling Problem (QCSP): In terminal operations, QCs are typically the most constrained resources. Hence, optimal schedules can maximize throughput, and minimize ship handling time (ship makespan). Several constraints need to be satisfied during the schedule generation process, such as preventing crane crossovers (structural constraint imposed on cranes and crane trajectory), maintaining a minimum distance between cranes (neighborhood constraint), time separation of containers that need to be stacked in the same location (job-separation constraint), and ensuring that unloading transactions within a ship bay precede loading transactions (precedence constraint defined by the stowage plan). Multiple optimization formulations have been developed with variations in task attributes (single or multiple bays), crane attributes (initial and final positions of the cranes, operational time windows), and interference attributes. Recently, container reshuffling and stacking area attributes (congestion constraints) have also been included in the models (Meisel and Wichmann, 2010; Choo et al., 2010). Legato et al. (2012) consider most of these constraints in a rich mixed-integer programming model. They solve the problem by a modified branch-and-bound algorithm which is based on the one developed by Bierwirth and Meisel (2009). Initial studies in this area generate QC schedules (unidirectional schedules) that consider non-crossing of cranes i.e., all QCs move in the same direction throughout the service. For instance, Lim et al. (2007) generate unidirectional SC schedules for complete bays. They model the QCSP using constructs from an m-parallel crane scheduling problem and develop a backtracking algorithm based on dynamic programming that generates optimal QC schedules for an average-size problems. Another stream of research allows the cranes to share the workload of bays, and develops optimal QC schedules for container groups. Lu et al. (2012) consider such a problem and solve it by developing an efficient heuristic which has a polynomial computational complexity. Queuing network models are also used to study the QCSP (Canonaco et al., 2008). The solution of such models are usually evaluated based on simulation. Meisel and Bierwirth (2011) develop a unified approach for evaluating the performance of different model classes and solution procedures.

Table 2 compares the existing QCSP models, based on another classification introduced by Bierwirth and Meisel (2010). The QCSP classification scheme also consists of four attributes: *task* | *crane* | *interference* | *performance measure*. Note that the classification does not cover studies employing simulation or analytical models such as the ones developed by Canonaco et al. (2008) and Meisel and Bierwirth (2011).

Table 2: Overview of QCSP formulations

Problem classification	Reference
$container, prec\|-\|-\|max(compl)$	Meisel and Wichmann (2010)
$bay\|-\|save, cross\|max(compl)$	Choo et al. (2010)
$group, prec\|ready, pos, move\|cross, save\|max(compl)$ related to the following two	Legato et al. (2012)
$group, prec\|ready, pos, move\|cross, save\ \|max(compl)$	Bierwirth and Meisel (2009)
$group, prec\|ready, pos, move\|cross, save\ \|w_1 max(compl) + w_2 \sum finish$	Kim and Park (2004)
$bay\|-\|cross\|max(compl)$	Lim et al. (2007)
$group\|move\|cross, save\|max(compl)$	Lu et al. (2012)

Note. References are sorted in order of appearance in the text. Abbreviations used in the table are:

Task attribute: *container*: containers, *prec*: precedence relations among tasks, *bay*: bays, *group*: groups of containers.

Crane attribute: *ready*: QCs have different ready times, *pos*: QCs have initial (and final) positions, *move*: travel time for crane movement is respected.

Interference attribute: *save*: safety margins between QCs are respected, *cross*: non-crossing of QCs is respected.

Performance measure: *compl*: completion time of a task, $finsih$: finishing time of a QC.

Unified berth and quay crane planning: The three problems: BAP, QCAP, and QCSP, can be solved in a sequential manner where the optimal berth plan (output from the BAP) serves as input to the QCAP. Likewise, the output (QCs assigned to a ship) along with the stowage plans form the input to the QCSP. However, sequential decision making may result in inferior quality solutions because of the interactions that exist among the decision variables. For instance, crane productivity and crane buffer positions affects ship handling times. A BAP, which is solved without considering QC dynamics, may overestimate or underestimate berth capacity requirements, thereby incurring opportunity costs for the container terminal.

To address these issues, three problems should be solved with a unified model, also termed as a deep integration. Meisel and Bierwirth (2012) develop a framework for integrating the three problems. First, they solve the QCSP for each ship with a varying number of QCs and determine the crane productivity rates. Next, these rates are included in a combined BAP and QCAP problem to determine the berthing position, berthing time, and crane capacity assigned to each ship. In the final stage, the QCSP is solved again and the time windows for the crane operations are established. Chen et al. (2012) also study the three problems in an integrated fashion and extend the integer model of Liu et al. (2006). To solve the problem, they use a Benders decomposition which decompose the problem into two problems denoted as master and slave problems. The master problem relaxes the associated QC constraints and determines the service start time, the number of assigned QCs, and the service completion time of each ship. On the other hand, the slave problem checks whether the output from the other problem is feasible in the sense that the non-crossing requirement among QCs are satisfied. They perform numerical tests and conclude that compared to CPLEX, their method obtains the optimal solution faster. Furthermore, if the CPLEX computing time is fixed to the amount of time that their method needs to compute the optimal results, the CPLEX solution is on average 76% worse than the optimal solution.

Stowage planning

To gain economies of scale and better ship utilization, ships sail from one port to another (up to 20 ports) through a fixed route. At each port, thousands of containers may be loaded, unloaded, or repositioned. While such container movement plans reduce the transportation cost per container, it poses a difficult operational problem known as the container stowage problem (CSP). A stowage plan includes the placement of a container at a ship slot described by a combination of the stack number, bay number, and tier number. The objectives of a good stowage plan are to minimize the port stay times of ships, ensure stability and obey stress operating limits of the ships, and maximize QC utilization. Several constraints have to be taken into account, such as container size, weight, height, port of unloading, and container type (reefer, danger class). The complexity of developing high quality stowage plans will further increase when shipping liners launch mega-ships with a storage capacity of 18,000 TEU or higher (for instance, see Maersk's "Triple E" series plan, Maersk Line, 2011).

Wilson and Roach (2000) classify the methodologies developed for addressing the CSP into five categories: 1) simulation based upon probability, 2) heuristic driven, 3) mathematical modeling, 4) rule-based expert systems, and 5) decision support systems. They also indicate that the existing solution methods either relax some of the important constraints or do not generate high quality solutions in a short time (also see Avriel et al., 2000). Further, existing models do not scale beyond small feeder ships of a few hundred 20-foot containers.

To deal with the complexity of the CSP, successful studies decompose the problem hierarchically into a multi-port master planning phase and a slot planning phase (Delgado et al., 2012). In the first phase (Master planning), the hatch-overstowage and crane utilization measures are optimized by determining the number of 20ft and 40ft containers that need to be stowed in a location. The integer programming model, which is shown to be $\mathcal{NP}$-hard, is solved using a relaxed MIP formulation. The second phase (slot planning) refines the master plan by assigning the containers associated with each location to a specific slot in the location. A constraint-based local search (CBLS) approach is used to solve the optimization problem.

3 Internal transport operations

The horizontal internal transport process connects the seaside and the stacking area processes by playing a dual role. Vehicles are used in the unloading process by transporting containers from seaside to the stacking area. They are also used in the loading process by transporting containers from the stacking area to the seaside area.

These vehicles for internal transport have varying degrees of automation and functionalities. We first review different types of vehicles. We then examine vehicle guide path types. The guide path has a significant impact on vehicle travel times and overall throughput performance. Further, we present innovations in information and communication technologies, such as vehicle tracking and tracing, that can help to improve coordination among vehicles. We then classify the different design decisions that affect vehicle transport performance, and discuss how OR tools can be deployed to analyze and to improve internal transport performance.

3.1 New technologies

Types of vehicles

Internal transport vehicles can be broadly classified into two categories: human-controlled and automated systems. Further, depending on the vehicle and crane transfer interface, the vehicles are classified as coupled (C) or decoupled (DC). Trailer-trucks and SCs are manual transport vehicles used in several container terminals in Asia (such as JNPT, India and Northport, Malaysia). Automated lifting vehicles (ALVs) and AGVs are used in automated container terminals such as the Patrick container terminal in Australia and the ECT container terminal in Rotterdam. Lift-AGVs (L-AGVs) are the recent innovation in the AGV family, which will be deployed at the new APM terminal at Maasvlakte II, Rotterdam (Gottwald Port Technology GmbH, 2012). We briefly describe these internal transport vehicles below.

Single-trailer or multi-trailer truck (C): These are used to transport single or multiple containers simultaneously.

Straddle carriers (DC): These are used to transport containers to the stacking area, and can stack containers up to three or four tiers. They are guided manually and have self-lifting capability.

Automated Guided Vehicles (C): These high-speed vehicles are used in automated container terminals to transport containers between seaside and the stacking area. For instance, automated terminals in the Port of Hamburg use a fleet of over 70 vehicles. AGVs can carry 20ft, 40ft or even 45ft containers. They have a high positioning accuracy and can travel forward, reverse, or sideways, and can overtake each other. The AGV navigation software manages vehicle travel along electromagnetic route markers (or transponders) that are embedded into the ground of the terminal. The vehicles have an automated refueling capability. Hybrid AGVs, with diesel-electric drive options are even more environmentally friendly.

Note that in an AGV transfer system, both the exchange of containers between the AGV and QC, and the AGV and YC is tightly *coupled*, because the AGV does not have a self-lifting capability.

Automated Lifting Vehicles (DC): These automated straddle carriers, also known as automated lifting vehicles (ALVs), decouple the container handling process between the seaside and the stacking area (Figure 7a). Due to their self-lifting capability, they are used in the unloading process, and pick up the containers from one of the several buffer lanes located beneath the QCs and transport them to the YC buffer locations. The new automated lifting vehicles can lift up to two containers at the same time.

Lift-Automated Guided Vehicles (C/DC): These are the latest innovation in vehicle transport. Lift-automated guided vehicles (L-AGVs) decouple the transport of containers to the stacking area processes (Figure 7b). "Compared with the conventional AGV, the L-AGV features a pair of electrically operated lifting platforms. These enable the vehicle to raise its load and deposit it independently and automatically on handover racks in the stacking crane interface zone and to pick up containers from those racks", Gottwald Port Technology GmbH (2012). They also claim that the fleet size can be considerably reduced as a result of the increased working frequency; the overall number of vehicles required to service each QC can be reduced by up to 50% compared with conventional AGVs.

L-AGVs and ALVs operate in a very similar way; they both transport containers and use decoupled interfaces at the stack and quay side. However, ALVs can also stack containers, while L-AGVs cannot.

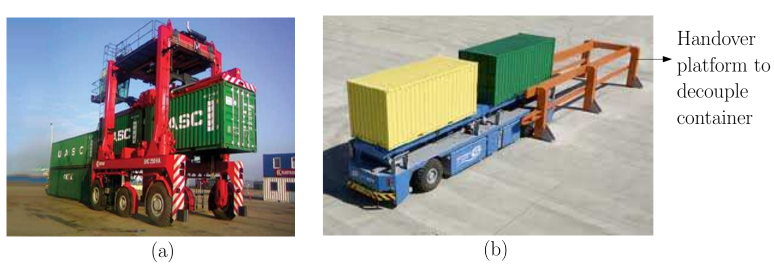


Figure 7: New internal transport vehicles: (a) Automated Lifting Vehicle, (b) L-AGV (Source: Gottwald Port Technology GmbH (2012))

Vehicle guide-path types

Automated vehicles travel a long guide-path in the yard area. Two types of guide-path networks are typically seen at container terminals: closed-loop and crosslane. The closed-loop guide-path is composed of several large circular guide-paths for vehicles to follow during travel (see Figure 8a-b). While a uni-directional closed loop travel path allows a simplified control of vehicles, it may increase vehicle travel time due to long travel distances. To gain speed during vehicle travel, most automated terminals now use guide-path networks with multiple cross-lanes (see Figure 8c-d). A crosslane path is composed of parallel travel paths with several big, small or mixed (both big and small) crossings. In crosslane guide-paths, a vehicle adopts the shortest travel path (using shortcut paths) from the quay buffer lane to the stack buffer lane and vice versa. Hence, cross-lane guide-path networks can significantly reduce AGV travel distances, but the complexity of controlling traffic (and hence, chance of blocking) at the intersection of paths increases.

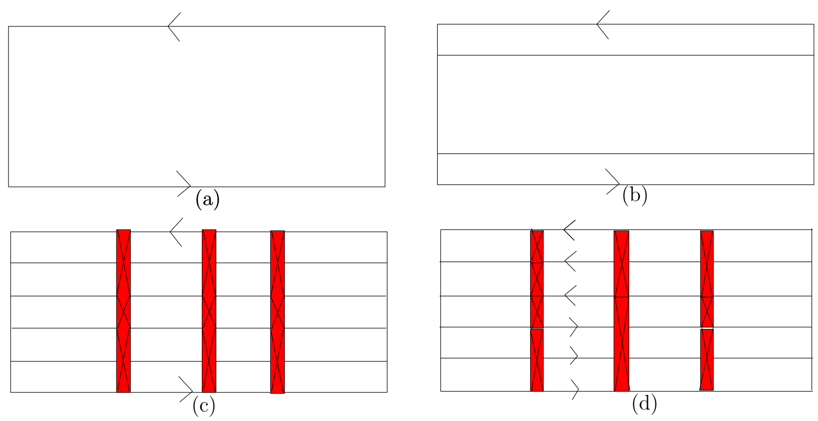


Figure 8: Types of vehicle guide-paths used for internal transport

Vehicle coordination and tracking

Better coordination among AGVs has multiple benefits for internal transport operations. A smaller fleet size can be used, and (empty) travel times can be reduced. Further, due to inherent operational variability in the system, QCs, vehicles or YCs may not be able to complete their service within the work schedule as planned by the terminal planners. In this regard, use of real-time resource status, which can be provided by automatic context capturing devices such as sensor networks, can help the terminal operators to re-plan the schedule. Today, several techniques exist for vehicle tracking and tracing, including the use of transponders, or GPS in combination with RFID. Ngai et al. (2011) develop an intelligent context-aware prototype for resource tracking in container terminals. Ting (2012) discusses the feasibility of applying RFID for vehicle tracking purposes in a container terminal. Hu et al. (2011) discuss RFID related tracking solutions for orderly balancing and seamlessly connecting different operational processes at the entrance gate of a container terminal.

3.2 OR models

Internal transport management

Optimization formulations have been developed to determine optimal fleet size and to decide on vehicle routing and operation schedules. Jeon et al. (2011) adopt a Q-learning technique to determine the shortest-time routes for internal transport using AGVs. Note that their approach also considers the expected waiting times that result from vehicle interference and the shortest-path travel times, to determine the optimal routes. Vis and Roodbergen (2009) consider the problem of scheduling SCs to process container storage and retrieval requests in the yard area. The two components of the problem are assigning transport requests to the vehicles and scheduling these requests for each vehicle. By using a combination of a graph-theoretic and dynamic programming approach, they solve the problem to optimality. Nguyen and Kim (2009) develop a mixed integer model for a terminal which uses ALVs to handle containers at the seaside. The objective is to minimize the total travel time of the ALVs and the total delays of QCs. They transform constraints regarding the buffer space under the QCs to time window constraints and propose a heuristic algorithm to solve the model.

Analytical models based on queuing theory have been also put to practice to study internal transport management. Kang et al. (2008) develop a cyclic queue model of container unloading operations that provides a steady-state throughput measure and can estimate the optimal fleet (cranes and trucks) size. The model assumes exponentially distributed service times in order to obtain closed-form analytical results. They also develop a Markovian decision problem (MDP) model that can dynamically allocate a transport fleet based on general service time distributions. Finally, through simulations, researchers have evaluated design choices and operational policies. Petering (2010) develops a simulation model to study the real-time dual-load yard truck control in a transshipment terminal.

Table 3 summarizes all these studies and specifies the type of vehicle considered in each study.

Table 3: Recent OR models on internal transport

Article	Research question/ area	Type of vehicle	Performance metric	Modeling approach
Jeon et al. (2011)	Determine shortest-time routes	AGV	Average travel time	Learning algorithm, simulation
Vis and Roodbergen (2009)	Sequencing requests	SC	Total travel time	Mixed integer programming
Nguyen and Kim (2009)	Vehicle dispatching using look-ahead information	ALV	Total travel time of ALVs and the total delays in QC operations	Mixed integer programming
Kang et al. (2008)	Fleet sizing	Truck	Total unloading time	Cyclic queues, Markov Decision Process
Petering (2010)	Real-time truck dispatching	Truck	QC gross rate	Simulation

Note. References are sorted in order of appearance in the text.

Gate operations planning

Terminal gates are the decoupling points of internal and external transport. Gate management is important, since the massive number of containers arriving and leaving terminals at the landside creates congestion. Many trucks and trains show up at the terminal gates for inland container transport. Trains have fixed schedules which are set externally. Violating these time windows is costly and container terminal operators prioritize trains so they can be easily loaded and unloaded to leave the yard. On the other hand, trucks are a more flexible, more efficient mode in door-to-door service for containers, but they bring higher cost (Wang and Yun, 2011). Modeling truck scheduling problems and their interaction with container terminal operations offers interesting challenges for researchers.

The long queues of trucks at the terminals lead to delays and cause emissions, congestion, and high cost. In the past several years, a growing number of studies have addressed truck congestion. One of the solutions is to carefully manage truck arrival times, using an appointment system in which a terminal operator announces the time periods that trucks can enter the terminal. Huynh and Walton (2008) develop a model to determine the maximum number of trucks a terminal can accept per time window. Huynh and Walton (2011) extend this model by additionally scheduling the trucks. Namboothiri and Erera (2008) study how a terminal appointment system affects the management of a fleet of trucks providing container pickup and delivery services to a terminal. The objective is to minimize transportation cost. Chen and Yang (2010) propose a ship-dependent time window optimization method, which involves partitioning truck entries into groups serving a specific ship and assigning different time windows to the groups. They use an integer programming model to optimize the position and the length of each time window and develop a genetic algorithm heuristic to solve the problem. Chen et al. (2013a) use several metaheuristic methods to solve the problem. Unlike the other studies, Lang and Veenstra (2010) consider congestion at the seaside. They develop a quantitative arrival scheduling simulation (centrally controlled by the terminal) to determine the optimal approach speed for the arriving vessels. Their cost function includes both fuel and delay costs.

Besides mixed-integer programming models, some studies use conventional stationary queueing models to analyze the gate system at container terminals (Guan and Liu, 2009; Kim, 2009). However, stationary queueing models should not be used to analyze a queueing system that is non-stationary in nature. The gate system at a container terminal is typical non-stationary, because the truck arrival rate varies from hour to hour and the gate service rate may change over time (Guan and Liu, 2009). Therefore, Chen et al. (2011b) propose a two-phase approach to find a desirable pattern of time varying tolls that leads to an optimal truck arrival pattern, by combining a fluid based queuing and a toll pricing model.

Table 4 summarizes all these studies and specifies the research questions and performance metrics considered in each study.

Table 4: Recent OR models on gate operations planning

Article	Research question/ area	Performance metric	Modeling approach
Huynh and Walton (2011)	Limiting truck arrivals (max is determined by Huynh and Walton, 2008)	Truck turn time and crane utilization	Simulation, optimization
Namboothiri and Erera (2008)	Pickup and delivery sequences for daily drayage operations	Transportation cost	Integer programming, heuristic
Chen and Yang (2010)	Time window management	Transportation as well as terminal operating costs	Meta-heuristic, Genetic Algorithm
Chen et al. (2013a)	Time window management	Truck waiting time, fuel consumption, cargo storage time, and storage yard fee	Queuing, hybrid meta-heuristics: genetic algorithm and simulated annealing
Lang and Veenstra (2010)	Vessel arrival planning, approach speed	Operational costs	Simulation
Guan and Liu (2009)	Gate congestion analysis	Gate operating cost, truck waiting costs	Multi-server queueing, optimization
Kim (2009)	Toll plaza design	Waiting time	Non-linear integer programming model, queuing model
Chen et al. (2011b)	Optimal truck arrival patterns	Total truck turn time and discomfort due to shifted arrival times	Queueing model, convex nonlinear programming model

Note. References are sorted in order of appearance in the text.

In general, terminal appointment systems have mixed performance. For example, Giuliano and O'Brien (2007) report unsuccessful application of a terminal appointment system at the Ports of Los Angeles and Long Beach. As a result, in addition to a gate appointment system, the operation research community should find new solutions to the gate congestion problem at terminals. Over the past decades, truck scheduling and storage allocation in port operations have been studied extensively as two separate subproblems. However, from the operational point of view, they are highly interdependent. Researchers might find better solutions when studying the two problems together. Van Asperen et al. (2011) have conducted a simulation experiment to evaluate the impact of truck announcement time on online stacking rules. The longer the announcement period, the better the performance of the stacking rules is. Similarly, Borgman et al. (2010) use simulation to compare the effect of different stacking rules on the number of reshuffles. They use given container departure times to minimize the number of reshuffles. Zhao and Goodchild (2010) assess how truck arrival information can be used to reduce the number of reshuffles when containers are retrieved to be loaded on the truck. The results demonstrate that significant container re-handle reductions can be achieved by using the truck arrival sequence obtained from the terminal appointment system, even if the sequence information does not cover all the trucks.

In addition to trucks, trains are also handled at terminals. However, the literature on train transportation focuses mainly on scheduling and routing trains outside the terminal, which is outside the scope of this review (see, for example, Wang and Yun, 2011; Woxenius and Bergqvist, 2011; Almotairi et al., 2011; Leachman and Jula, 2012; Newman and Yano, 2000; Yano and Newman, 2001; Cordeau et al., 1998). On the other hand, a handful of papers discuss train loading and unloading operational problems. Most of these papers focus on handling trains at transshipment yards which are designed to move containers from trains to trucks and vice versa, which is again outside the scope of this review (see, for example, Jaehn, 2012).

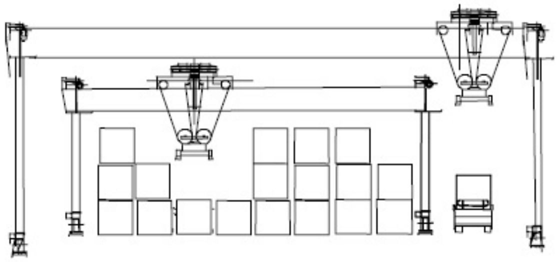
4 Stacking area operations

The stacking area is one of the most important areas at a container terminal, since almost every container spends a period of time in this area. The operations performed in this area affect the performance of the whole terminal. Many stacking decisions must be made daily. In the past, container terminals used traditional container handling equipment such as straddle carriers and reach stackers to stack and retrieve containers in the stacking area. However, these types of equipment cannot serve the huge number of containers that nowadays arrive and leave terminals. Today, most large new container terminals use yard cranes to handle containers in the stacking area. Therefore, we mainly focus on YC operations in the following sections.

4.1 New technologies

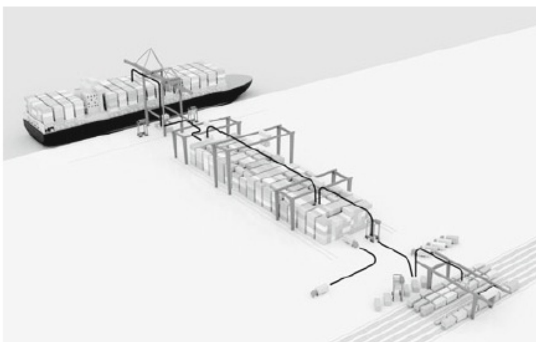
Yard cranes

New container terminals use two or three YCs to retrieve and stack containers in every stack, as shown in Figures 9a-c (Li et al., 2009; Vis and Carlo, 2010; Li et al., 2012). Depending on the design of the stacks and YCs, the YCs can or cannot pass each other. There is a fixed safety distance between YCs during stacking operations. Twin 40 feet QCs have been used in automated container terminals for several years. However, YCs with twin lifting capabilities have only been introduced recently. Zhu et al. (2010) study a new type of YC designed by Shanghai Zhenhua Heavy Industries that can lift two 40 feet containers at the same time (see Figure 9d).

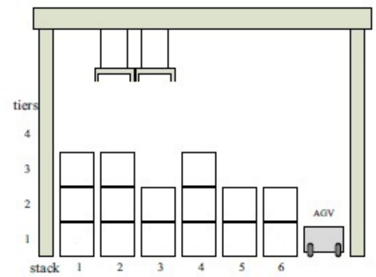


(a) Passing double YCs (Source: Vis and Carlo, 2010)

(b) Non-passing double YCs also known as twin YCs (Source: NauticExpo, 2012)



(c) Triple YCs (Source: Dorndorf and Schneider, 2010)



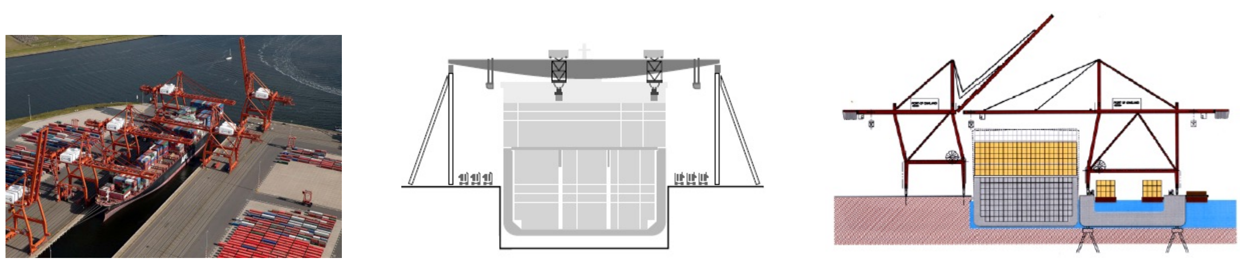
(d) Twin lifting YC (Source: Zhu et al., 2010)

Figure 9: Twin, Double, triple, and twin lifting YCs on a container stack

New container terminal layouts and stacking systems

In new automated container terminals, containers are generally stacked in container stacks which can be perpendicular or parallel to the quay. Obviously, the size of the stacks, the number of stacks, and the type of material handling equipment can be different. Many papers have recently studied the effect of these layout variables on the performance of the terminal. Kim et al. (2008) develop an integer programming model to determine the layout type, the outline of the yard, and the numbers of vertical and horizontal aisles. Wiese et al. (2011) develop a decision support model for the design of yard layouts of SC-based terminals. However, the dominant methodology in such papers is discrete event simulation because it is difficult to capture all elements and find an optimal solution. Petering and Murty (2009) develop a simulation model for a transshipment yard. They find out that in order to keep QCs busy and minimize the makespan of ships, the block length should be limited between 56 and 72 TEU. Furthermore, the movements of the YC should be restricted to one block. Petering (2011) extended the simulation study to include decision support for yard capacity, fleet composition, truck substitutability, and scalability issues. Kemme (2012) develop a simulation study to evaluate the effects of four RMG crane systems and 385 yard block layouts, differing in block length, width, and height, on the yard and terminal performance. Lee and Kim (2013) compare two terminal layouts that differ in the orientation of the stack blocks with respect to the quay: a perpendicular layout and a parallel layout. They consider different cost factors including the construction cost of the ground space, the fixed overhead cost of yard cranes, and the operating costs of yard cranes and transporters. The effect of various design parameters on the throughput capacity and storage space capacity of the designs is evaluated.

In all the papers discussed so far containers are loaded and unloaded by QCs from only one side of the ships. At a terminal with an indented berth, containers can be loaded and unloaded from the ship at both sides (see Figure 10a). Some of these terminals have special QCs spreading over the indented area carrying out the operations (see Figure 10b). Furthermore, terminal operators can use floating QCs to form a temporary indented berth (see Figure 10c). Chen et al. (2011a) develop an integer programming model to schedule QCs loading and unloading containers of a ship in an indented berth. They propose a Tabu search to solve the problem. Vis and Van Anholt (2010) develop a simulation model for a similar setting. They argue that an indented berth results in more flexibility. In addition, if all equipment is scheduled properly, an indented berth can lead to shorter makespan of the ship. However, the QCs can be used less flexibly compared to conventional quays, as they cannot easily move to other quay positions. In addition, using many cranes per ship may lead to a low productivity per crane, due to blocking from two sides of the ship. It may therefore be difficult to financially justify such operations. Recently, Imai et al. (2013) study terminals with different indented berth design servicing both feeders and mega-ships where mega-ships have priority to feeders. They conclude that a straight berth performs better in terms of reducing the handling time of feeders. On the other hand, an indented berth design where ships can enter from one side and exit from the other side performs better in terms of reducing the handling time of mega-ships.



(a) Indented berth with QCs at both sides (Source: Young, 2012)

(b) QC spreading over an indented berth (Source: Jordan, 1997)

(c) Floating QCs (Source: Jordan, 2002)

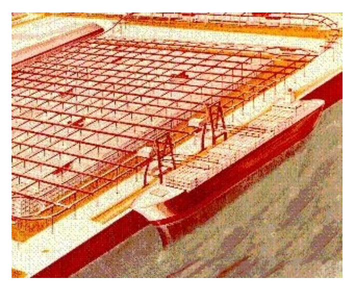
Figure 10: Different indented berth designs

Another layout suggested to increase performance is to add a chassis exchange terminal to a terminal or a group of terminals (Dekker et al., 2012b). A chassis exchange terminal reduces the congestion at the main terminals by handling trucks externally. During the night, import containers are collected from the terminal and loaded on chassis. During the day, these chassis are exchanged with chassis loaded with export containers. Since trucks can quickly charge or discharge chassis, the capacity of the terminal increases substantially. However, Guan and Liu (2009) argue that due to land requirements, more feasibility studies are necessary to justify its application.

Reviewing the literature on warehouse layout design reveals that in order to obtain more flexibility and a higher performance, designs in which stacks and transfer lines are diagonal to the quay, or in which stacks are divided into smaller stacks with different sizes and I/O points in the middle should be studied (Öztürkoğlu et al., 2012; Gue and Meller, 2009; Gue et al., 2012). In warehouses, such new layouts have achieved a reduction in vehicle travel time of up to 20% (Öztürkoğlu et al., 2012). Recently, container terminal managers have started to adopt new stacking systems stemming from warehouse literature, such as rack-based compact storage, or overhead grid rail systems. Ez-Indus of South Korea has built a prototype of an ultra-high container warehouse (UCW) system (see Figure 11a). The UCW is a high-rise rack-based automatic system that can theoretically save 90% of the space by stacking containers up to 50 tiers high. Containers are delivered to the UCW where they are placed on shuttles. These take containers into the UCW elevator which takes them to a slot in the rack. Shuttles can also be used to transfer containers between the seaside and landside, as show in Figure 11b. These shuttles can move containers to the UCW or to the traditional container stacks. In the overhead grid system shown in Figure 11c, containers can be handled using the cranes hanging from the overhead grid. The new systems may result in a higher container terminal efficiency. However, the cost of implementing such systems is very high, as terminals deal with large and heavy containers compared to small and light totes in a warehouse. The question is therefore whether such systems can become profitable in the long term.

(a) Ultra-high container warehouse system (Source: Ez-Indus)

(b) Shuttle system (Source: Zhu et al., 2010)



(c) Overhead grid rail system (Source: Kosmatopoulos et al., 2002)

Figure 11: New stacking systems

4.2 OR models

Yard crane operations planning

At a container terminal, Yard cranes (YCs) move retrieval containers from the block to the input and output (I/O) points, and move storage containers from the I/O points to the block. Due to huge number of containers handled at terminals, YCs often deal with a queue of containers waiting to be stacked or retrieved. It is therefore important to minimize the makespan and total delay time of all requests to be carried out by a YC by optimally sequencing them. In the following, we review some of the recent OR models developed for scheduling YCs.

Yard crane scheduling: In general, YCs can be classified into two types: rail-mounted gantry (RMG) cranes and rubber-tired gantry (RTG) cranes. RTG cranes are manned and can move freely from one stack to another. RMG cranes can be automated or manned, and their movements are limited to one or a few adjacent stacks in a row. Automated RMG cranes are sometime called automated stacking cranes (ASCs), according to Stahlbock and Voß (2008b). A survey by Wiese et al. (2010) using the data of 114 container terminals, worldwide, shows that 63.2% of all terminals use YCs for stacking. In Asia, this is 75.5%.

Most of the papers dealing with YC scheduling do not specify any special type of YC (i.e., manual or automated RMG or RTG crane), and as such the models and solution methods developed are applicable to all sorts of YC. However, the assumptions considered often show that the models are more suitable for a special type of crane and usually need to be modified for another type of crane. Table 5 summarizes recent integer programming models (other than the ones mentioned in Stahlbock and Voß, 2008a) on YC scheduling including the objective functions and constraints considered. We try to indicate the type of crane considered based on the constraints mentioned in the papers.

Table 5: Recent integer programming OR models on single YC scheduling

Paper	Request type	Objective function (to minimize)	# stacks	# YCs	Specific assumptions	Solution method	Crane Type
Kim and Kim (1999)	Retrieval	Makespan	Single/adjacent stacks in a row	Single	Containers with different types and without a retrieval sequence	An exact algorithm	RMG
Narasimhan and Palekar (2002)	Retrieval	Makespan	Single/adjacent stacks in a row	Single	Containers with different types and a retrieval sequence	B&B, heuristic with a worst-case performance ratio of 1.5	RMG
Chen and Langevin (2011)	Retrieval	Makespan	Adjacent stacks in a row	Multiple	Containers with different types and a retrieval sequence, non-passing cranes	Genetic algorithm and tabu search	RMG
Guo and Huang (2011)	A set of jobs including retrieval and storage	Minimize the average vehicle job waiting time at yard side	Adjacent stacks in a row	Multiple	Crane interference constraints, comparing the results with Ng (2005)	A combination of simulation and optimization	RMG
Froyland et al. (2008)	Retrieval and storage	Smooth utilization of RMGs	Adjacent stacks in a row	Multiple	Other objectives including minimizing long dwell time and maximum number of SCs	Decomposition heuristic	RMG
Zhang et al. (2002)	Retrieval and storage	The total delayed workload	Multiple	Multiple	Crane interference constraints	Lagrangean relaxation	RTG
Cheung et al. (2002)	Retrieval and storage	The total delay time of requests	Multiple	Multiple	Crane interference constraints	Lagrangian decomposition and successive piecewise-linear approximation	RTG
He et al. (2010)	Retrieval and storage	The total delay time of requests, the number of times that YCs move among stacks	Multiple	Multiple	Crane interference constraints	Genetic algorithm employing heuristic rules	RTG
Chang et al. (2011)	Retrieval and storage	The total delay time of requests	Multiple	Multiple	Crane interference constraints	Heuristic algorithm	RTG

Recently, Sharif and Huynh (2012) employed agent-based models to formulate the YC scheduling problem. Agent-based models can dynamically adapt to real-time truck arrivals, making them better suited for real-life operations. Vidal and Huynh (2010) also use an agent-based approach to schedule YCs with a specific focus on assessing the impact of different crane service strategies on drayage operations. In their work, they model the cranes as utility maximizing agents and develop a set of utility functions to determine the order in which individual containers are handled. Finally, Petering et al. (2009) develop a simulation model for the real-time YC control in transshipment terminals.

Scheduling two or three YCs dedicated to a stack: In the previous section, we focused on papers in which each stack has a single YC or in which stacks share YCs. We now review papers in which stacks with double or triple YCs are considered.

Li et al. (2009) introduce a discrete time model to schedule twin YCs carrying out storage and retrieval requests in a single stack. The YCs cannot pass each other and must be separated by a safety distance. The requests have different due times and the objective is to minimize a weighted combination of earliness and lateness of all requests, compared to their due times. They introduce a rolling horizon algorithm in which a horizon of a specific length is defined, and all requests falling within this horizon are considered and optimized by CPLEX. The horizon is updated whenever all its requests have been scheduled. In a recent paper, Li et al. (2012) extend the model to a continuous time model. The results show a significant improvement compared to a previous discrete model. Park et al. (2010) consider container rehandling (see Section 4) in their mixed-integer programming model used for scheduling twin YCs in a rolling horizon mode. Containers that have to be rehandled are considered as independent requests and are assigned to any idle YC. This approach results in balancing the workload of YCs and reducing the waiting times of trucks and AGVs. Vis and Carlo (2010) consider a double YC problem in which the YCs can pass each other but cannot work on the same bay simultaneously. In their problem, requests do not have any due time and can be scheduled in any sequence. They formulate the problem as a continuous time model and minimize the makespan of the YCs. They solve it by a simulated annealing algorithm and use the single-row method proposed by Vis (2006) to compute a lower bound. Cao et al. (2008) propose an integer model for a similar problem. They develop two heuristics and a simulated annealing algorithm to solve the problem. Stahlbock and Voß (2010) perform a simulation study to investigate to what extent double YCs can help to improve a container terminal efficiency. They evaluate different online algorithms for sequencing and scheduling requests. The experiments are based upon real world scenarios (from the Container Terminal Altenwerder, CTA, Hamburg, Germany).

Recently, Container Terminal Altenwerder (CTA) in the Port of Hamburg installed three cranes per stack to handle stacking operations (Dorndorf and Schneider, 2010). Two cranes are smaller so that the larger crane can pass (see Figure 9c). Dorndorf and Schneider (2010) model the scheduling problem of these cranes as an integer programming model. The objective is to maximize the productivity of the crane system under peak load while preventing delays in the transport of import and export containers. They solve the problem in a rolling horizon scheme using a beam search method. The results show that the method performs better than nearest neighbor and first-come-first-served request selection heuristics by more than 20%.

Minimizing container reshuffling

New technologies and methods for managing the stacking area of container terminals reduce the container throughput time. However, a discussion about improving the efficiency of container stacking would be incomplete without considering container reshuffling. A reshuffle is an unwanted movement of a container stacked on top of the one which has to be retrieved (Kim et al., 2000; De Castillo and Daganzo, 1993; Caserta and Voß, 2009b). Reshuffling is one of the daily operations at a container terminal and is time consuming and increases a ship's berthing time. Few systems, such as the UCW discussed above, allow direct access to all containers. However, not much technological innovation can be seen in this regard. On the other hand, many new methods have been designed to reduce or avoid reshuffling. Papers dealing with container reshuffling study three main subjects: (1) pre-marshalling, (2) relocating methods while retrieving containers, and (3) stacking methods.

The common objective in all these papers is to reduce the number of reshuffles.

Pre-marshalling: Some researchers focus on how to reduce the number of reshuffles by pre-marshalling containers in a way that fits the ship's stowage plans. Pre-marshalling is the repositioning of containers of the stack so that no or few reshuffles are needed when containers are loaded onto the ships. Lee and Hsu (2007) propose an integer programming model for a container pre-marshalling problem preventing reshuffles. They develop a multi-commodity network flow model for obtaining a plan on how to pre-marshal containers stacked in a single bay and solve it by replacing some of the constraints and relaxing others. They also propose a simple heuristic for large-scale problems. Lee and Chao (2009) develop a neighborhood-based heuristic model to pre-marshal containers of a single bay of a container stack in order to find a desirable final layout. Caserta and Voß (2009b) propose a dynamic programming model to pre-marshal containers of a single bay. In order to quickly find the solution, they propose a corridor method. In this local search method, a pre-marshaled container of a specific pile can only be stacked in a corridor which consists of the next few predecessor or successor piles of the bay with a specific limit on the number of empty locations. Expósito-Izquierdo et al. (2012) develop an instance generator which creates instances with varying degrees of difficulty. The difficulty of the instances is determined based on the occupancy rate and the percentage of containers with high priority that are located below those with low priority. Bortfeldt and Forster (2012) propose a tree-based heuristic to solve the pre-marshalling problem. In the tree search procedure, the nodes of the tree represent layouts. The root node corresponds to the initial layout and each leaf node corresponds to a final layout. Finally, Huang and Lin (2012) work on two different types of container pre-marshalling problems, and develop two heuristics to solve them. They obtain better solutions than the solutions present in the literature (i.e., Lee and Hsu, 2007) in a shorter time.

Relocating: The problem of minimizing the number of reshuffles of a container stack while containers are retrieved is called the block (stack) relocation problem (BRP), which is proven to be $\mathcal{NP}$-hard by Caserta et al. (2012). Given a retrieval sequence of containers in the BRP, the decision is where to locate reshuffled containers to obtain the minimum number of reshuffles when all containers in the retrieval sequence are retrieved. Caserta et al. (2011) formulate the problem as a DP model and use a corridor method similar to the one proposed by Caserta and Voß (2009b) to solve it. Since the quality of the solution depends on the length and height of the corridor, in two later papers, Caserta and Voß (2009a) and Caserta and Voß (2009c) incorporate heuristic algorithms to tune these variables. Caserta et al. (2009) propose a greedy heuristic algorithm to solve the BRP. In their heuristic, a reshuffled container will be stacked either in a pile which is empty or in a pile of containers that have lower retrieval priority. If such a pile is not available, the container will be stacked in a pile of containers that have a retrieval time nearest to the container that has to be stacked. Forster and Bortfeldt (2012) propose a tree search algorithm similar to the one developed by Bortfeldt and Forster (2012) for the pre-marshalling problem. However, they use a finer move classification scheme, different rules for branching and bounding, and require an additional greedy heuristic. Finally, Lee and Lee (2010) consider a multi-bay generalization of the BRP and describe a solution approach that combines heuristics with integer programs.

Stacking: Although pre-marshalling and relocating help to minimize the number of reshuffles while containers are retrieved, a good stacking policy significantly decreases the handling effort in later stages. Some papers focus on how to avoid reshuffling by proposing methods to properly locate incoming containers in a container stack. Dekker et al. (2007) investigate different stacking policies, using simulation based on real data. They allocate containers to the stack based on the container's expected duration of stay. Kim and Park (2003) also propose a heuristic algorithm based on the container's duration of stay to locate export containers. Kim et al. (2000) propose a stochastic DP model for determining storage positions of export containers in a single bay of a stack. To avoid solving a time consuming DP model for each incoming container, they build decision trees, using the optimal solutions of the DP model. The trees decide where to store an incoming container. The validity of the recursive function of the DP model is proven by Zhang et al. (2010). Saurì and Martìn (2011) propose three new strategies to stack import containers. They also develop a model to compute the expected number of reshuffles based on the container arrival times. They compare their strategies based on different criteria including the size of terminals and container traffic. Yu and Qi (2013) consider a similar problem. They propose two models of which one is used to allocate import containers to the stack after they are unloaded from a ship, and the other one is used to pre-marshal containers. Through simulation, they validate the models and find out that segregating the space and pre-marshaling enhance the efficiency of the terminal in terms of reducing truck waiting times. Finally, Casey and Kozan (2012) develop a dynamic mixed-integer programming model to determine where to stack containers while others are retrieved in each period. The objective is to minimize the total amount of time that containers are stacked in the block. Several constraints are developed to calculate the amount of required time for reshuffling, loading and unloading containers from the equipment systems handling the containers.

5 Hinterland operations

Large deep-sea terminals face many challenges such as congestion, delay, and pollution. This has driven container terminals to transform their supply chains to increase their competitiveness and robustness (Vervest and Li, 2009; Heinrich and Betts, 2003). By closely collaborating with hinterland terminals, deep-sea terminals can balance flows and workload more efficiently over time. As a result, not all the value adding activities, such as container inspection and container delivery to end-customers, need to be done at deep-sea terminals, but can be postponed to hinterland terminals.

5.1 New technologies

Close cooperation of deep-sea and hinterland terminals is a recent development, caused by the enormous increase of the number of containers handled (Heaver et al., 2001; Notteboom and Winkelmans, 2001; Notteboom, 2002; Robinson, 2002; Van Klink and Van den Berg, 1998; Roso et al., 2009). At first, the goal was to increase the capacity by adding "dry ports" to the main deep-sea terminals. During the last decade, the amount of authority delegated to these hinterland terminals has increased. Veenstra et al. (2012) describe an example project in Rotterdam which integrates supply and transportation by extending the sea terminal gate into the hinterland. An extended gate is an inland intermodal terminal directly connected to seaport terminal(s) with high capacity transport mean(s), where customers can leave or pick up their containers as if directly at a seaport (including customs and security inspections), and where the seaport terminal operator can choose to control the flow of containers between the terminals. Iannone (2012) empirically studies another example in the Campania region in Southern Italy. He claims that in order to achieve greater competitiveness and sustainability, it is essential to call for private and public actors to take up various initiatives and adopt policies.

5.2 OR models

Network configurations give rise to several strategic and operational problems such as information sharing, modal split, and inter-terminal transportation, repositioning of empty containers, asset-light solutions, and barge operations which were not a matter of concern previously. We discuss these topics in more detail below. Due to the novelty the operations research-related literature on this topic is still limited, providing an opportunity for future research.

Information sharing

One of the crucial conditions for the development of efficient networks is the availability of reliable information on containers (arrival, departure times, content, and modes of final transport). Terminal operators usually only have estimated arrival and departure times. More exact information can be used to better stack containers, to minimize internal travel time to the proper pick up points, and to avoid lateness or earliness of loading and unloading different modes of transport. Some examples were discussed in the previous sections (see, for example, Van Asperen et al., 2011; Borgman et al., 2010). Douma et al. (2009) propose a decentralized multi-agent system to align barge operators with terminal operations. They compare their approach with a central approach, where a trusted party coordinates the activities of all barges and terminals. The results indicate that, in spite of the limited information available, their approach performs quite well compared to the central approach. In their later study, Douma et al. (2011a) examine the effect of different degrees of cooperativeness on the efficiency of the barge handling process.

Modal split and service network design

One of the most important challenges in a container handling and transport network is the modal split. Besides ships, terminal operators deploy trucks, trains, and barges to transport containers. Barges and trains have less negative environmental and societal impact than road transport. However, compared to trucks, barges and trains usually have longer transit times, and do not connect directly to any final destination (Groothedde et al., 2005). Port authorities are strongly urging container terminals to adopt more environmentally friendly modes of transport. For example, the Port of Rotterdam needs to move from the current truck/barge/rail split of 45/40/15 percent to 35/45/20 percent by 2035 (Veenstra et al., 2012; Port of Rotterdam Authority, 2012).

Over time, the seaport terminals are being integrated with inland terminals, by means of frequent services of high capacity transport modes such as river vessels (barges) and trains. The multi-modal transport operators typically face three interrelated decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacity of the transport means and frequency of service, and (3) set the prices for the transport services on the network (Ypsilantis and Zuidwijk (2013)). Van Riessen et al. (2013) propose an integer-programming model for the design of such networks. The model uses a combination of a path-based formulation and a minimum flow network formulation that penalizes overdue deliveries and combines both self-operated and subcontracted services. Sharypova et al. (2012) address the minimum cost service network design problem by developing a continuous-time mixed-integer linear programming model. Using this model, they are able to accurately determine transportation events and the number of containers to be transshipped by vehicles. Ypsilantis and Zuidwijk (2013) propose a bi-level programming model to jointly obtain the design and price of extended gate network services for profit maximization.

Inter-terminal transportation

Inter-terminal transportation is the movement of containers between close-by terminals (by sea, rail, or otherwise), often in the same port area. When developing new terminals and container ports, the movement of containers between terminals has to be taken into consideration. Previous work in the area of design and evaluation of the inter-terminal transportation commonly deals with simulation (see, for example, Ottjes et al., 2007). Recent work use optimization methods to study the problem. Tierney et al. (2013) develop a model combining vehicle flows and multi-commodity container flows for inter-terminal movements. They solve the model to optimality using real data from the Port of Hamburg, Germany, and the Maasvlakte 1 & 2 area of the Port of Rotterdam, The Netherlands. Lee et al. (2012) develop a mixed-integer programming model for assigning ships to terminals within a terminal hub and allocating corresponding containers. The objective function is to minimize the total inter-terminal and intra-terminal handling costs. They develop a two level heuristic algorithm to solve the problem. Minimizing intra-terminal handling costs is also considered in the BAP problem studied by Hendriks et al. (2012).

Stacking empty containers in hinterland terminals

Empty containers are generally not stacked at the main deep-sea terminal, due to scarcity of land. However, they have to arrive at the terminal on time so that they can be loaded on ships to be transported to destinations where they are needed. Furthermore, they have to be transported away from the terminals in time to make space for other containers. Liner shipping companies have been dealing with this problem for a long time. They need to explicitly take the repositioning of empty containers in their global service networks into account. Successful studies have been conducted in this regard. For example, Compañì a Sud Americana de Vapores (CSAV), one of the world's largest shipping companies, has saved $81 million by optimizing its empty container logistics (Epstein et al., 2012). CSAV developed a multi-commodity multi-period model to manage container repositioning, and an inventory model to determine the safety stock required at each location. Similar models have been studied by other authors such as Cheung and Chen (1998); Crainic et al. (1993); Choong et al. (2002); Shintani et al. (2007), and Erera et al. (2009). Despite the present literature for repositioning of empty container in liner shipping service networks, one needs to note that the specific practical constraints required for such a problem in a network consisting of closely located deep-sea and hinterland terminals call for new analytical methods. For example, the number of containers that can be handled within a port network by barges, trains, and trucks is small. Therefore, multiple transport modes have to be scheduled and routed so that containers can arrive on time. Furthermore, due to the geographical dispersion, the level of freedom in the order in which ports are visited by ships to pick up or deliver empty containers is much more limited than within a port.

Asset-light solution

Multiple sea and inland terminals are often connected in a network with line-haul connections and different modes of transport (trains, trucks, and barges). In an asset-light solution, terminals use the empty space of such transport modes to opportunistically transport containers that are prone to delay, but are scheduled for later transportation, or containers that are required unexpectedly at destinations. If time windows assigned to transport modes are not violated, such a strategy decreases total cost and increases efficiency. Almost none of the vehicle routing models with multiple vehicle types and capacities, designed to schedule movements among terminals in a network, exploit such empty capacity of transport modes (see, for example, Lee et al., 2012).

Barge transportation

During the past decades, truck transport has been the dominant mode of inland transportation compared to train and barge. To reduce the pressure on the current road infrastructure as well as to reduce greenhouse gas emissions, port authorities aim for a modal shift from road to barge or train. For a country with easy access to waterways, barge transport is a competitive alternative to road and rail transport due to its ability to offer cheap and reliable transport services. One of the crucial conditions for successful barge freight transportation is the alignment of terminal and barge operators. The barge handling problem (BHP) consists of routing and scheduling barges to visit different terminals in a port. A centralized decision making method, where a trusted party coordinates the activities of all barges and terminals, is acceptable by neither terminal nor barge operators. Generally, they are not willing to share information and want to be autonomous. Therefore, online decentralized decision making methods are much more suitable in this case. To achieve this goal, Douma et al. (2009) model the problem using agent based planning systems and compare their approach with a central approach. The results indicate that, in spite of the limited information available, their approach performs quite well compared to the central approach. The authors extend this idea in their later studies (Douma et al., 2011a,b). The insights from these studies are currently imbedded in a project entitled barge terminal multi-agent network (BATMAN) which will be implemented in the Port of Rotterdam (Mes, 2012). Despite the intriguing findings and clear contributions, the present studies are not enough to capture all aspects of such operations in practice. There is an opportunity for the academic community to explore barge operations more deeply.

6 Emerging research areas

In this section, we identify new research areas in container terminal operations that require the development of OR models, and which have a significant practical relevance from the view of design and operations planning.

6.1 Integrating operations

Container handling operations in a terminal requires integrated coordination from QCs, vehicles, YCs, and gates at the seaside, stacking area, and landside. The terminal resources need to be coordinated effectively and the interactions among them need to be understood well. Due to the sheer complexity of a container terminal system, researchers have mostly analyzed and optimized subsystems in isolation. Optimization and simulation models have been developed to address operational issues in isolated systems as discussed in the previous sections. However, they do not guarantee the development of an optimal integrated terminal system.

Due to novelty and complexity of this topic, the literature is scarce. Recently, Zhen et al. (2011) combined the berth template planning that is concerned with allocating berths and quay cranes to arriving vessels (the QCAP and BAP discussed in Section 2), and yard template planning that is concerned with assigning yard storage locations to vessels. They develop an integer programming model and propose a heuristic to solve it. The objective function is to minimize the delay of ships and total travel time of transshipment containers in the yard. Another integrated problem at the seaside is studied by Lee and Jin (2013) who propose a mixed-integer programming model combining three tactical problems including: (1) berth allocation, (2) allocation of preferred service time windows for cyclically visiting feeders, and (3) allocation of storage yard space to transshipment flows between mother vessels and feeders. They solve the problem by a memetic algorithm. Bae et al. (2011) have compared the operational performance of an integrated system with two types of vehicles (ALVs and AGVs). Through simulation studies they show that the ALVs reach the same productivity level as the AGVs using far fewer vehicles due to their self-lifting capability. Through simulation studies, they show that the ALVs achieve the same productivity level as the AGVs using far fewer vehicles due to their self-lifting capability. Cao et al. (2010) propose an integrated model for yard truck and yard crane scheduling problems for loading operations in container terminal. They formulate the problem as a mixed-integer programming model and propose two solution methods based on general and combinatorial Benders decompositions to solve it. To evaluate the model, they generate 20 random instances based on the layout of the Keppel Terminal in Singapore. The combinatorial Benders cut-based method can obtain an optimal solution for instances up to 500 containers, 60 trucks and 40 cranes within 45 minutes, which is efficient for daily operations. Chen et al. (2013b) study a similar problem and formulate it as a constraint programming model. They propose a three-stage solution method where yard cranes are scheduled first, then yard trucks are routed, and the complete solution is obtained in the final stage. Finally, Zeng and Yang (2009) consider the holistic problem of determining the loading or unloading sequence, scheduling, and dispatching QCs, YCs, and yard trucks simultaneously. In order to solve the problem, they develop a framework which combines simulation and optimization.

Although integrated models offer new possibilities for container terminal analysis, they are complex. It seems that deterministic models do not offer sufficient possibilities to handle the complexity needed, without making overly restrictive assumptions. Stochastic models might therefore offer a way out, at least in the design conceptualization phase of a terminal. Recently, Roy and De Koster (2012a) has developed an integrated queuing model to analyze the design choices in seaside operations. The model is useful for analyzing the impact of vehicle dwell point, effect of stack configuration and vehicle guide path design on throughput times. This model is extended to design optimal terminal layout with AGVs (Roy and De Koster, 2012b).

6.2 Terminal operating systems and simulation

All new technological and methodological advancements are useless without suitable software to run them. Nowadays, many companies such as TBA BV, Cosmos NV, and Navis provide terminal operating systems (TOSs) that streamline container operations. A TOS is a software system that helps to plan, track and monitor all container movements at the terminal, from arrival until departure, including booking, document handling and invoicing. TOS systems in many cases have simulation and emulation capabilities. As it is also discussed in Section 6.1, due to the complexity and intrinsic uncertainty involved in problems considering integration and interaction of different systems at a container terminal, discrete event simulation is useful in analysis and setting decision rules.

According to Petering et al. (2009), more than 40 papers on simulation models can be found in the literature which range from strategic to operational decision making. Some of the recent ones include: Hadjiconstantinou and Ma (2009), Petering and Murty (2009), Petering et al. (2009), and Petering (2010, 2011), which were discussed in the previous sections. Reviewing the literature reveals that advanced three-dimensional graphical simulation models are not abundant. The models developed provide little flexibility in altering the design parameters, and are restrictive in understanding the effect of a large range of design choices on system performance. Developing easy-to-use and graphical simulation models may provide an interesting research opportunity for the scientific community. Although simulation studies in the literature try to capture a holistic view of the terminal by integrating different systems, they are still restrictive in the view that they only focus on one or two systems. More sophisticated studies which simulate multiple systems are needed.

6.3 Green terminals

Sustainability, next to efficiency, has recently caught the attention of academic and professional communities (Geerlings and van Duin, 2011). Traditional models in the literature, which consider only profitability and efficiency, have to be modified to include broader considerations of the terminal's internal and external stakeholders and its environmental impact. This will result in many new tactical and operational problems, some of which are discussed next. Unfortunately, only few papers on container terminal operations focus on sustainability issues.

Sustainable container terminal design: The first step in making container terminals more sustainable is to redesign container handling equipment. The main typical questions in this regard are the type and size of equipment, and energy choice. Traditional QCs, YCs, trucks, and SCs handling containers at terminals consume vast amounts of fuel which result in CO2, CO, SO2, NOx, HC, and PM emissions. The average fuel consumption of traditional manual YCs ranges between 20 and 30 liters of diesel per hour (Zrnić and Vujičić, 2012). In peak hours, the amount can exceed 100 liters per hour. The result is more than 350 tons of CO_2 emissions per year (based on the commonly used diesel calorific value with a density of 830-850 kg/m^3 at 15 °C) (Zrnić and Vujičić, 2012). Assuming 14 operational hours per day, it is easy to calculate that a YC emits more than 1.2 tons of CO_2 per day, and also 6.3 kg of NOx, 1.7 kg of HC, 1.2 kg of SO_2, and 0.7 kg of PM. Container terminals are currently investing heavily in new technologies to reduce the fuel consumption of container handling equipment, often under pressure of port authorities (see the previous subsection).

Terminals are also promoting more sustainable energy sources including wind, sun, and biomass instead of gas and coal. Further, energy must be consumed in a sustainable way. Several energy saving installations such as sophisticated lighting systems and solar cells can be designed for terminals. Manufacturers of container handling equipment are now propagating electrically operated equipment. Recently, Dekker et al. (2012a) indicated several areas where environmental aspects could be included in operations research models for logistics. In this regard, the literature reviews by Corbett and Kleindorfer (2001b), Corbett and Kleindorfer (2001a), Kleindorfer et al. (2005), Sarkis et al. (2011), Srivastava (2007), and Sbihi and Eglese (2010) can also be mentioned.

Internal container handling: Sustainability introduces a new genre of operational questions to internal container handling operations. For example in routing and scheduling problems, speed used to be the most important factor to minimize cost and to satisfy time window constraints at destination ports. Nowadays, reducing fuel consumption and emissions has become important, while at the same time demand has to be satisfied. A second example is the scheduling of multi-trailer trucks. Compared to straddle carrier transport, using these trucks can result in lower CO_2 emissions. However, properly scheduling multi-trailer trucks is more difficult, as all containers should be available. Otherwise, a multi-trailer truck cannot perform its operations and containers encounter delay.

External container handling: Some studies deal with other external container handling modalities including barges, trains, and trucks. In general, barges are more CO_2 efficient than trucks or trains, and trains are more CO_2 efficient than trucks. Bloemhof et al. (2011) analyze environmental performance of different modes of transport. Based on the sustainability assessment criteria initially proposed by Jeon and Amekudzi (2005), they develop several sustainability measures and carry out a case study on electric push barges. They conclude that barge transportation achieves good performances on economic, social, and environmental aspects due to its inherent ability to transport high volumes. They also conclude that sustainable developments in rail and road transports are more innovative than in barge transport. Environmental effects should be included in future models studying external container handling problems such as the modal split problem discussed in Section 5.

Terminal location: Within OR there is a whole stream of research on facility location, which mainly deals with the number and location of facilities. The main objective in the models is the minimization of cost and maximization of customer satisfaction. Considering the huge amount of movement betweens terminals specially in network oriented models where many containers are transported between inland and deep-sea terminals, in addition to all the other costs, CO2 emissions costs should be considered in the model.

6.4 Security

Handling containers involves many sorts of security risks, such as terrorist attacks and smuggling. Although the probability of such incidents is relatively low, the costs can be extremely high. As an example, Abt (2003) estimates that detonation of a nuclear device in a port could result in losses ranging from $55 to $220 billion. Despite the importance of port security, only a handful of papers in the operations research-related literature of container terminal operations deal with the subject. The reason is that it is difficult to quantify security and the data available is highly confidential. Recent events such as the terrorist attacks of September 11, 2001, have shifted the port security focus from smuggling to terrorist threats. Flynn (2004) and Flynn (2007) review port security issues and actions taken to increase it. Government documents are a comprehensive source for background information on port-security measures (see, for example, U.S. Government Accountability Office, 2005, 2008c,b,a).

Currently, in order to assure security, the common objective in many ports and especially in the U.S. is to inspect every container arriving and leaving a terminal (Bakshi et al., 2011). In order to inspect containers, most of the terminals use X-ray scanners which cost approximately $4.5 million each with estimated annual operating costs of $200k (Frankle, 2004). Almost 5% of scanned containers require additional inspections (Schiesel, 2003; McClure, 2007; Marine Link, 2004). However, due to logistics and jurisdiction related problems, the actual number of containers inspected manually at international ports is much lower. The physical inspection of a container may take hours involving 15–20 inspectors (Bowser and Husemann, 2004) or three days for five agents (Johnson, 2004). Screening all containers is costly and time consuming causing delays for transporting containers. Therefore, container terminal operators are looking for new inspection strategies that are fast and financially viable, and at the same time can maintain the same security level (Harrald et al., 2004; Willis and Ortiz, 2004; Wasem et al., 2004).

Wein et al. (2006) develop a mathematical model to find the optimal inspection strategy subject to constraints of port congestion and overall budget. The aim is to find the level of investment in detection equipment and personnel required to meet a safety target, given a predefined flow of containers to be inspected. The results show that using detection equipment at ports from where containers are shipped provides significant cost savings. Martonosi et al. (2005) evaluate the feasibility of 100% container scanning at U.S. ports. They conclude that a 100% scanning with current technology is not feasible because of restrictions on land and personnel. If personnel and land considerations are negligible, then scanning 100% of all containers is cost effective for attacks with estimated costs greater than $10 billion. Similarly, Bakshi and Gans (2010) use game theory models to study container inspection policies at U.S. domestic ports. Furthermore, Bakshi et al. (2011) perform a simulation study to compare two container inspection regimes, namely the container security initiative (CSI) and the secure freight initiative (SFI). CSI employs rule-based software to identify high risk containers destined for U.S. ports. These high-risk containers are then screened. Under SFI, all U.S. bound containers arriving at participating overseas seaports are scanned. Their results show that the SFI regime provides better inspection coverage than CSI at a lower unit cost.

7 Conclusions

During the last decade, container terminals have witnessed rapid developments that have led to the design of more automated, responsive, cost- and energy-efficient, and secure terminals. Operations research models encompassing new constraints and objective functions enforced by such advancements are required to efficiently manage container terminals. The operations research community needs to revisit and update the previous studies on container terminal operations. This paper discusses the new developments in container terminal technologies and OR models, and reviews the related literature. Although the study is limited to container handling operations performed inside a terminal, this paper shows that there is a huge body of research on the related topics and there is enough room for further research.

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