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Storage yard operations in container terminals: Literature overview, trends, and research directions

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ABSTRACT

Inbound and outbound containers are temporarily stored in the storage yard at container terminals. A combination of container demand increase and storage yard capacity scarcity create complex operational challenges for storage yard managers. This paper presents an in-depth overview of storage yard operations, including the material handling equipment used, and highlights current industry trends and developments. A classification scheme for storage yard operations is proposed and used to classify scientific journal papers published between 2004 and 2012. The paper also discusses and challenges the current operational paradigms on storage yard operations. Lastly, the paper identifies new avenues for academic research based on current trends and developments in the container terminal industry.

1. Introduction

Container terminals can be divided into five main areas, namely the *berth*, *quay*, *transport*, *storage yard*, and (*terminal*) *gate*, as illustrated in Fig. 1. The berth and the quay areas are considered *seaside*, while the storage yard and gate areas are considered *landside*. The *transport* area is at the intersection of the seaside and landside areas. This paper describes the latest trends, developments, on storage yard operations in container terminals and classifies relevant literature.

The unloading process at container terminals can be described as follows. Vessels arriving at container terminals are assigned to a berth. Upon mooring, vessels are unloaded by one or more quay cranes according to an unloading plan. Containers are then relayed to transfer vehicles, which transport them to the storage yard where they are temporarily stored (typically) by yard cranes. Depending on their destination, containers might be transshipped to another vessel, or dispatched via the terminal gates for transport by trucks or trains after being inspected. The loading process at container terminals is the reverse of the unloading process, except that the loading is done according to a loading (or stowage) plan. Typically, the loading of the vessel occurs after the unloading process is completed. The logistical challenge for container terminals arises as at any point in time there might be several moored vessels, some of which are being unloaded and others loaded. Terminal managers aim in operational decision making to minimize vessels' turnaround times while meeting agreements with shipping companies. For a more detailed description of all the decisions made in container terminals the readers are referred to Vis and De Koster (2003) and Steenken, Voß, and Stahlbock (2004).

The goal of this paper is to introduce a classification scheme for the storage yard operations at container terminals, to review recent literature and to identify new avenues for academic research based on current trends and developments. We distinguish between the following main decision problems that arise in the storage yard operations: (1) yard design, including material handling equipment (MHE) selection and storage yard layout; (2) storage space assignment to containers; (3) MHE dispatching and routing to serve the storage and/or retrieval requests; (4) optimizing the reshuffling of containers. These topics will be treated in this order in this paper, since from a yard design and usage point of view, these aspects follow each other more or less in chronological order; a yard must be designed before it can be operated, and a container's storage locations must be assigned before equipment can be dispatched to put it there. All decisions potentially influence each other mutually, and therefore papers that address this decision interaction will be treated once all separate decision problems have been clearly outlined.

This paper is the first to propose a formal classification scheme for storage yard operations. Luo, Wu, Halldorsson, and Song (2011) is the only other literature overview paper dedicated to storage yard operations. However, Luo et al. (2011) is limited to summarizing a subset of the existing storage yard operations literature. In that sense, Luo et al. (2011) provides a literature update to the overview papers of Vis and De Koster (2003), Steenken et al. (2004), and Stahlbock and Voß (2008) which review all operations

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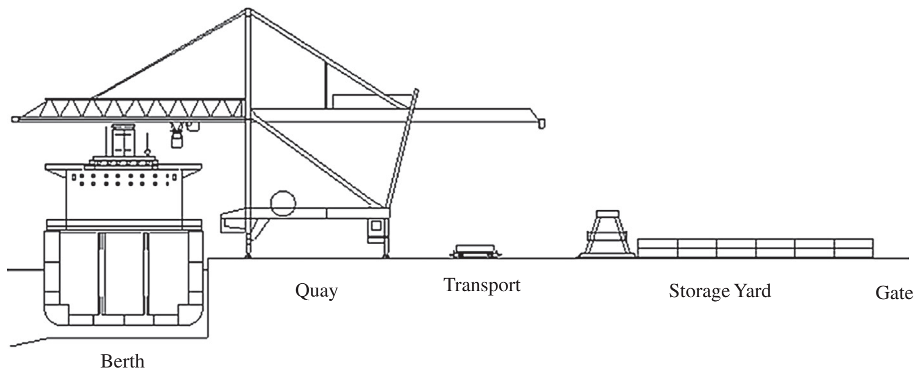

Fig. 1. Container terminal main areas.

in container terminals. In terms of the literature overview we limit ourselves to articles published and available as in press between 2004 and 2012, whereas this paper is a partial follow up to Vis and De Koster (2003). An extensive search in several scientific databases including Engineering Village, Google Scholar, Pro Quest, and Web of Science resulted in 90 scientific journal articles, published in 36 different journals, directly related to container terminal storage yard operations. Note that publications addressing two emerging decisions related to storage yard operations (i.e., container inspections and intermodal operations) are not discussed in this paper. Also, publications addressing the management of refrigerated and empty containers are not treated in this paper.

The remainder of the paper is organized as follows. Section 2 presents an introduction to storage yard design and operations. Section 3 presents our classification scheme for the storage yard operations literature. Next, we provide an in-depth overview of the pertinent literature, divided by decision problem. In Section 4, we first go into literature on yard design. Control rules (2)–(4) are then presented in Sections 5–7, followed by a discussion in Section 8 of the integration of two or more of the base decision problems. In Section 9 we take a step back to reconsider the storage yard operations from an Industrial Engineering and Operational Excellence perspective to challenge the current operational paradigms. Lastly, Section 10 presents research avenues based on current trends and developments in the container terminal industry.

2. Introduction into storage yard operations

The goal of this section is to discuss storage yard operations and relevant industry trends and developments in terms of the material handling equipment (Section 2.1), layout (Section 2.2), and operational strategies (Section 2.3).

2.1. Material handling equipment

Frequently used material handling equipment in the storage yard is the gantry (yard) crane (GC), shown in Fig. 2a. There are two types of gantry cranes, rubber-tyred gantry cranes (RTGCs) and rail-mounted gantry cranes (RMGCs). RTGCs are typically non-automated as they have the flexibility to travel freely within and between blocks. RTGCs are able to rotate the tires 90° to perform orthogonal moves known as *cross gantrying*. However, cross gantrying is a very slow process that takes approximately 15 minutes. On the other hand, the movement of RMGCs is limited by its (underground) rails.

A survey of the available container terminal data online by Wiese, Kliewer, and Suhl (2009), also included in Wiese, Suhl, and Kliewer (2011) found that RTGCs were used as the main stacking MHE in 63.2% of the 114 container terminals studied. Automated RMGCs are known as automated stacking cranes (ASCs). ASCs are able to completely operate without human interaction as long as they interact with automated transfer vehicles. However, if ASCs are to interact with non-automated vehicles (e.g., external trucks), the pickup (and deposit) moves from (to) non-automated vehicles is done manually for safety reasons. Based on results from the same study, Wiese et al. (2011) point out that 6.1% of the terminals considered use automated RMGC (ASCs) most of which were located in Europe. The (distant) second most used material handling equipment (MHE) in the storage yard is the straddle carrier (20.2%, see Wiese et al., 2011), shown in Fig. 2b. Straddle carriers (henceforth referred to as SCs) are non-automated transport vehicles that are capable of self-lifting and stacking containers. Given the self-lifting and stacking capability of SCs some container terminals use them for both transferring containers between the quay and the storage yard, and for storing containers in the yard.

In order to increase the throughput of storage yards, multiple gantry cranes may be used in collaboration. There are two types of gantry crane arrangements, passing and non-passing gantry cranes. The passing cranes arrangement, also known as *double* or *dual*, uses one crane that is larger than the other. This allows for the smaller crane to pass under the larger crane as long as the hoist for the larger crane is not down. Passing configurations are currently exclusively used with ASCs given the precision required for passing. Container Terminal Altenwerder (CTA) in the Port of Hamburg, Germany, has implemented this passing cranes concept. We will use the term *dual passing RMGCs* to refer to this configuration.

The non-passing gantry cranes arrangement is composed of two identical gantry cranes (*twin GC*) that must maintain a minimal safety distance from each other (Klein, 2011) and typically serve one area of the yard (Saanen, 2011). The twin GC configuration may occur with RMGCs and RTGCs. If the twin GC is automated, we refer to the system as *twin ASC*. Twin GCs may collaborate by using a (flexible) exchange zone. In this setting, for example, the one crane could retrieve a container on one side of the yard and move it to an exchange point. Then, the other crane could retrieve this container from the exchange point and deliver it on the other side. An example of a terminal that uses twin GC is the Euromax terminal in the Port of Rotterdam, The Netherlands.

In general, it is easy to show that if both cranes travel at the same speed, the dual passing RMGCs arrangement will always have a throughput at least as high as the twin GCs arrangement. However, in reality, the larger RMGC in the passing arrangement is typically slower than the smaller RMGC, which moves at the same speed as the twin GCs. As an extension to the two-crane arrangement, a new triple-crane was introduced in Container Terminal Burchardkai (CTB) in the Port of Hamburg, Germany. The

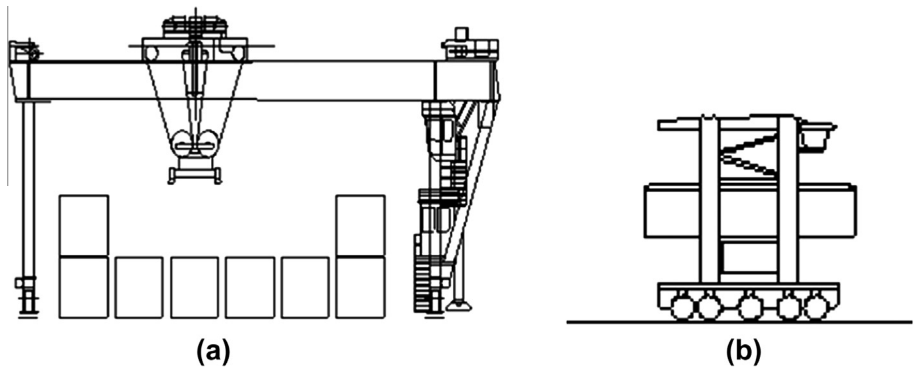

Fig. 2. Storage yard MHE: gantry crane (a) and straddle carrier (b).

triple crane configuration is composed of two non-passing RMGCs with a larger passing RMGC. In the triple crane configuration the passing crane typically works in the middle to facilitate containers for the twin GCs on each side.

One of the largest challenges for automated storage yards is that they need to be synchronized with the container transport operation. Two new types of technology allow the storage yard operations to be asynchronous with the transport operations. A new *Lift-AGV*, developed by Gottwald (2013), uses electrically operated lifting platforms that enable the AGVs to raise (or lower) containers automatically to pick up (deposit) them to a frame. A new type of self-lifting automated straddle carrier, called Autostrads, could influence container terminals to return to straddle carrier layouts. This type of straddle carrier is used at Patrick container terminal in Brisbane, Australia. Another development in the storage yard is the multi-lift spreader for gantry cranes and the twin capacity straddle carrier. These technologies allow MHE to handle more than one container at the same time.

A development in terms of storage yard equipment is the capability to remotely operate gantry cranes. Although ASCs are capable of operating completely automated, when the system is to interact with non-automated entities, it is common to perform interactions in a semi-automated manner for safety reasons. In other words, a crane operator either takes over the ASC to complete the transfer or approves the movement for the ASC to continue (e.g., Kim, 2006b). In Section 4 we describe methods for MHE selection.

2.2. Layout

A typical yard layout consists of multiple rectangular blocks. Material handling equipment (see Section 2.1) serves one or multiple blocks. A typical block consists of several rows of containers, each consisting of bays. Containers can be stacked in tiers up to several containers. (*Note:* both bays and blocks are sometimes referred to as stacks in literature.) Fig. 3 presents a block layout design with 6 rows and 16 bays, stacked in tiers of up to 2 containers. The number of rows, bays, and tiers in a block depend on the type of equipment used. In Section 4 we describe literature tackling yard and block layout design.

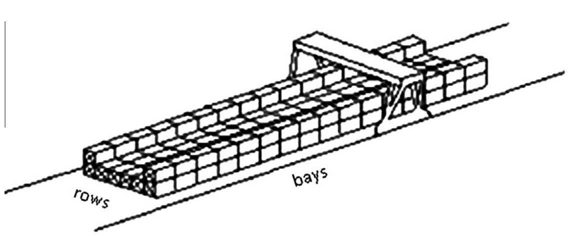

Fig. 3. Storage yard block.

There are two main configurations of yard layouts for gantry cranes (Lee & Kim, 2013; Liu, Jula, Vukadinovic, & Ioannou, 2004; Petering, 2008). The main difference is in the location of the input/output (I/O) point, i.e., where the transfer vehicle and the yard crane exchange containers, the relative positioning of the blocks to the quay and typically the level of automation used.

The first configuration, mainly used in non-automated storage yards, has blocks positioned parallel to the quay (see Fig. 4a). Typically, one or more rows in each block are reserved as truck lanes. Internal and external transfer vehicles (e.g., trucks) travel in the truck lane(s) until they reach the bay associated with the (storage or retrieval) request they are serving. In this configuration, the gantry crane travels to the truck lane to pick up (or deposit) containers to (from) the transfer vehicle. This kind of layout is quite common in large Asian terminals. Hence, for convenience, we refer to them as the Asian layout.

The second configuration, typically used in automated yards, have blocks positioned perpendicular to the quay (see Fig. 4b). The I/O points are located at both ends of the storage blocks to respectively handle storages and requests from the seaside and landside. Typically, automated guided vehicles (AGVs) are used to pick up and deposit containers at the seaside I/Os, while external trucks are used at the landside I/Os. This layout configuration was first implemented in some large European container terminals. Henceforth, for convenience, we refer to this layout configuration as the European layout.

Compared to the Asian layout, the European layout has higher investment cost, lower operational costs, faster crane speeds (including travel and pickup and deposit times), more storage capacity per area (since the cranes are wider and do not require truck lanes), and minimizes the distance travelled by transfer vehicles and external vehicles at the expense of longer yard crane travel distances. To compensate for the larger travel distances, the ASCs are typically required to accelerate and decelerate quickly, which becomes harder and more costly as yard blocks get wider. In practice, particular attention is given to increasing the storage yard throughput, as improving the storage yard integration with transfer vehicles and external trucks (Kalmar, 2013).

Fig. 5 presents a typical straddle carrier layout. Different from the gantry crane layouts, the straddle carrier layout has some separation between rows in a block so the straddle carrier may move within rows. Some authors refer to the arrangement of containers in the straddle carrier layout as linear stacking (e.g., Brinkmann, 2011, chap. 2). In this layout, containers are placed in rows stacked typically between 1 to 5 tiers high with the I/O points are at the end of the blocks. In Fig. 5, we show lanes that are positioned in parallel to the quay. However, also for straddle carrier layouts it

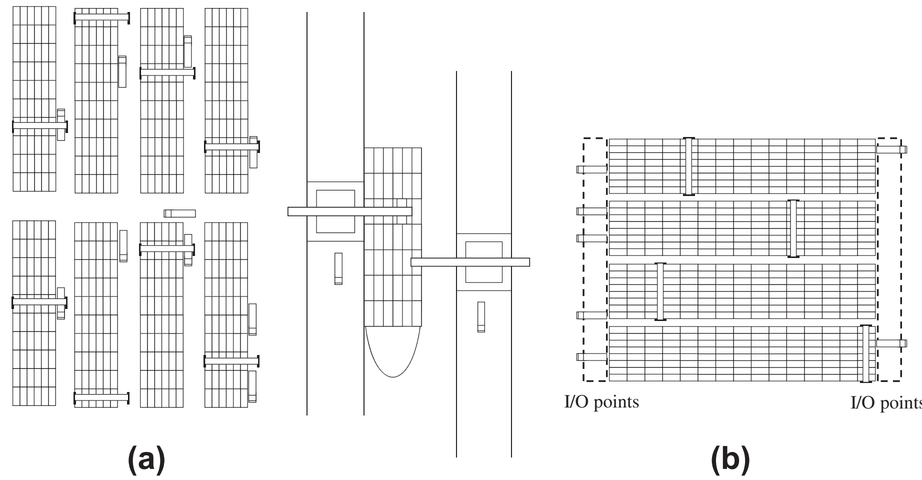

Fig. 4. Asian (a) and European (b) storage yard layout.

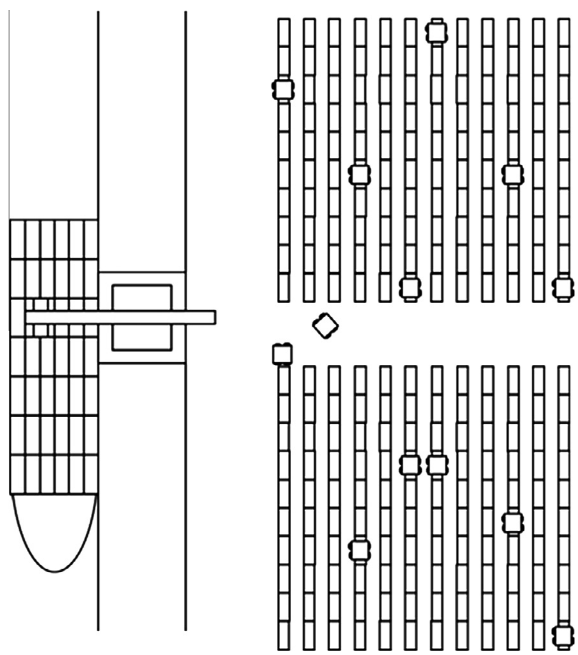

Fig. 5. Storage yard layout for straddle carrier.

holds similar to gantry crane layouts that lanes can be positioned perpendicular to the quay.

An interesting trend to handle import and export containers is to have rail access within the container terminal's yard. In terminals with vessel-train intermodal operations, containers are retrieved from the landside and moved by internal transfer vehicles to a rail-crane to load/unload containers to the train. These trains are typically used to transfer containers from the container terminal to an external storage location located inland in order to increase the container terminal's storage capacity, reduce truck congestion, or to open the containers to add value or reconsolidate the freight. These external storage facilities are typically called *inland ports* (Harrison, Prozzi, McCray, & Henk, 2002).

2.3. Operations

Typical operations in the yard include storage and retrieval of containers. Related decision problems are storage assignment of containers and dispatching and routing of material handling equipment. ASCs are commonly operating under double-cycling policies (i.e., serving a storage request, followed by a retrieval request). On the other hand, double-cycling is not a common practice in Asian layouts. The main reason is that in Asian layouts dedicated block areas (i.e., one or more contiguous bays) might be used. Dedication means that specific areas are dedicated to containers with the same characteristics including the same assigned vessel, dimensions, weight, container type, and destination (Saanen & Dekker, 2011). In Section 6 we focus on dispatching and routing of MHE.

Containers with the same characteristics are referred to as a *container group* (or *class*). In general, containers within a group are not distinguished in the vessel stowage plan. In fact, in the vessel loading plan, containers from the same group are more propense to be loaded together. Hence, some ports use the *consignment strategy*, which assigns containers bound to the same group (or even vessel) to be consolidated in the same storage area (Saanen & Dekker, 2011). Consignment is more common in pure transshipment terminals (i.e., sea to sea) and particularly beneficial for Asian layouts operating with RTGCs as retrieving containers from the same yard-bay is efficient in that configuration (Saanen & Dekker, 2011). Clearly, using the consignment strategy will require more storage space since a dedicated storage assignment policy is applied to reserve block areas for specific vessels, typically resulting in lower storage space utilization than when, for example, random policies are used (De Koster, Le-Duc, & Roodbergen, 2007).

On the other hand, for European layouts it is not necessarily beneficial to store containers in the same bay, but rather to store them closer to the I/O points at the end of the block. Notice that European layouts have seaside and landside I/O points. To improve the storage yard operations during vessel loading, European layouts tend to favor moving containers from their current storage location to a location closer to the desired I/O. These moves are called *repositions*. In Section 5 we describe storage space assignment models in more detail.

If an area within the block is reserved for containers bound to the same vessel, repositioning containers to this area is referred to as *remarshaling* or *housekeeping*. Also, given the additional travel time in European layouts, containers bound to the same vessel are often distributed among blocks seeking an even yard-block work balance (Saanen & Dekker, 2011). Another phenomenon found in storage yards is *reshuffling* (also known as *rehandles*, *relocations*, or *shuffles*). Reshuffles are unproductive moves required to gain access to a desired container that is blocked with other containers over it. In Section 7 we show that papers seem to put an emphasis on designing methods to reduce reshuffles or incorporate them as requests for the MHE. When container terminals know the sequence in which containers will be retrieved, reshuffling occurs to organize the containers so that no further reshuffling is needed to retrieve all containers. This process, known as *premarshaling*, typically occurs during gantry crane idle time. Refer to Section 7 for more details on academic output in this area.

Another operational phenomenon that has been carefully monitored in storage yards is congestion. Congestion is particularly important in Asian layout, which have longer transfer vehicle cycle times. A trend in Asian layouts is to carefully consider traffic congestion when selecting yard blocks for storage. On the other hand, congestion is much less for European layout because of the shorter travel distances at both the sea and landside of the terminal.

3. Classification scheme for storage yard operations

The proposed classification scheme with six groups of mutually exclusive attributes is presented in Table 1 and described below. These attributes will help characterize and position the publications by explicitly stating the decisions and modeling assumptions used. The main reason for having mutually exclusive attribute levels is that it describes what the papers address and do not address. The scheme can be easily encoded and separated by vertical bars (i.e., tuplets) or it can be presented by using tables. In this paper we use a table to classify the papers. Clearly, the proposed classification scheme can be easily updated as the research area evolves, by adding new attributes.

The *Decision Problem Attribute Group* considers seven attributes: *stocap*, *stoassig*, *routing*, *dispatch*, *compare*, *reshuffle*, and *layout*. These attributes specify if the storage capacity requirement, storage space assignment, MHE routing, MHE dispatching, type of storage yard MHE, reshuffling, and storage yard layout, respectively, are considered decision variables in the models.

The *Yard Layout Attribute Group* characterizes the layout assumptions made. Attributes *asian* and *european* are used to specify if the Asian or European layouts are assumed (see Section 2). If neither the Asian nor the European attributes are selected (i.e., they have a value of "0"), the straddle carrier layout is implied. For papers that describe a GC-based layout but do not specify which one we use a dash in both Asian and European attributes. The *3D* attribute is used to specify if the third dimension (i.e., height) of the storage yard is taken into consideration. In general, this attribute is used when reshuffling is considered. Attribute *grouped* is used to specify if the container demand is specified in terms of a container group as opposed to specific containers. If containers are not grouped, the models can be seen as a special case, where there are as many groups as containers.

The *MHE Characteristics Attribute Group* characterizes the MHE considered (see Section 2). Attribute *dedicated* is used to specify that the MHE is dedicated to specific blocks. Attributes *straddle*, *RTGC*, and *RMGC* specify the three most common types of MHE

Table 1
Proposed storage yard operations classification scheme.

	Attribute	Description
Decision problem attribute group		
1	*stocap*	Storage space capacity is a decision problem
2	*stoassig*	Storage space assignment is a decision problem
3	*routing*	Routing of MHE is a decision problem
4	*dispatch*	Focus on dispatching policies for MHE
5	*compare*	Focus on comparing MHE
6	*reshuffle*	Number of reshuffles is a decision problem
7	*layout*	Focus on finding the best storage yard layout
Yard layout attribute group		
8	*Asian*	Consider Asian layout (i.e., with truck lane)
9	*european*	Consider European layout (i.e., I/O points at ends)
10	*3D*	The height of the stacks is considered (e.g., reshuffling)
11	*Grouped*	Container requests are for container group (not individual)
MHE characteristics attribute group		
12	*dedicated*	MHE is dedicated to one block
13	*straddle*	Straddle carriers are used as storage equipment
14	*RTGC*	RTGCs are used
15	*RMGC*	RMGCs are used
16	*singlecrane*	A single crane per block is used
17	*dualpass*	Dual passing RMGCs arrangement is used
18	*twinGC*	Twin (non-passing) GCs arrangement is used
19	*triple*	A triple crane arrangement is used
Temporal attribute group		
20	*readyd*	Container ready (i.e., available) times are assumed deterministic
21	*readys*	Container ready (i.e., available) times are assumed stochastic
22	*dued*	Container due times are assumed deterministic
23	*dues*	Container due times are assumed stochastic
24	*horiz*	The planning horizon is dynamic
Uncertainty environment attribute group		
25	*stochop*	Stochastic optimization is used
Performance measure attribute group (to minimize)		
26	*num*	Associated with the number of moves required
27	*compl*	Associated with task completion time (typically makespan)
28	*dist*	Associated with MHE distance travelled-related metrics
29	*due*	Associated with due times-related metrics
30	*space util*	Utilization of yard space
31	*GC util*	Utilization of gantry cranes
32	*other*	Other metrics or particular metric not enforced

used. Attributes *singlecrane*, *dualpass*, *twingc*, and *triple* specify the crane arrangement used, which indicates the use of a single crane, dual passing RMGCs, twin (non-passing) gantry cranes, or the three-crane configuration (two non-passing and one passing), respectively (see Section 2).

The *Temporal Attribute Group* indicates if the containers' ready times are deterministic (*readyd*) or stochastic (*readys*), if due times are deterministic (*dued*) or stochastic (not known beforehand) (*dues*), and if the planning horizon is dynamic (*horiz*). Generally, ready times are given by the (expected) arrival of a transfer vehicle to the storage yard. Notice that *readyd* and *readys* are mutually exclusive, but not exhaustive as ready times might not be considered. A similar situation occurs with due times. On the other hand, if the planning horizon is not dynamic, then it must be static.

The *Uncertainty Environment Attribute Group* only contains one attribute to indicate if stochastic optimization is used (*stochop*).

Lastly, the *Performance Metric Attribute Group* shows the most used terms in the objective function and could be related to some weighted linear function of: the number of moves performed by the MHE (*num*); the completion times (*compl*); the distance travelled (*dist*); due times (*lateness*); utilization of yard space (*space util*); utilization of the gantry cranes (*GC util*)or other metrics (*other*). Other metrics refer to papers where the objective function, or some term in the objective function, does not fall into any of the other attributes, or is not specified.

Sections 4–8 include an in-depth overview of literature. The classification of all papers is presented in Appendix A.

4. Yard design

We distinguish between two decisions in the design of the storage yard which together make its physical appearance, namely: (1) equipment selection and (2) layout design. As explained in Section 2 there is a direct relation between the type of equipment selected and the configuration of the yard expressed in the number of blocks, rows and bays and stacking height. In general, the storage yard layout to be implemented is determined after deciding the level of automation and MHE to be used. At the same time, the level of automation required is affected by the expected throughput, capital investment, and the operating costs in the country in which the terminal will be located. The MHE to be used is also affected by the type of containers to be handled and the dimensions of the terminal. Given outcomes for each of those aspects, finding a good storage yard layout is not a complex problem. However, in practice, the storage yard layout problem needs to be combined with the problem of selecting the MHE. We first discuss papers addressing equipment selection and continue with papers studying the layout problem as well as papers studying the integrative problem.

4.1. Equipment selection

The proper material handling equipment (MHE) for each container terminal depends on many factors, which were discussed in the previous sections. Papers in literature mainly focus on understanding under which conditions one MHE outperforms the others. Simulation, cycle time estimates or a combination of both are common techniques to be used in those comparative analyses.

Vis (2006) presents a simulation study to compare SCs with ASCs operating in an European yard in terms of the expected total time to retrieve a set of storage and retrieval requests, including (rectilinear ASC) travel, hoisting, and expected reshuffling time. Experimental results show a clear link between the block layout and the MHE used. ASCs outperform SCs if the number of (parallel) rows for each crane is between six and eight. If more than nine rows are used, the author expects SCs to outperform ASCs. Dell, Royset, and Zyngiridis (2009) compare single and twin GCs considering reshuffling and housekeeping by means of proposing new solution approaches and performing a simulation study. The main performance criteria are the number of requests served and the idle time. For the twin (non-passing) ASCs, it is assumed that ASCs do not collaborate via an exchange zone (see Section 2.1). Interference between the ASCs is handled by having ASCs that cross the mid-way point of the block to wait until the other ASC is not in the way. After an ASC crosses the mid-point of the block it has priority over the other crane. Experimental results based on the Port of Rotterdam, The Netherlands, using a 15-minute rolling horizon, found that in this case two ASCs outperform a single-ASC by up to 70%.

Gantry crane cycle-time estimates may be used to estimate the expected queue length, as well as other gantry crane performance indicators. Kim (2006a) provides an estimate for the expected cycle-time of an ASC, including reshuffling times, by considering the different movements required for GCs to serve requests. The cycle-time estimates are derived for Asian and European layouts, as well as for randomized and consignment storage strategies. It is assumed that the ASCs operate under Chebyshev travel (i.e., actual travel time equals the maximum of the horizontal and vertical travel time). Lee and Kim (2010a) extend the work of Kim (2006a) by providing expected cycle-time and variance estimates for Asian and European layouts, under Chebyshev and rectilinear movement. Using the derived formulas is it shown that expected cycle-time for Chebyshev travel are shorter than with rectilinear travel and that the Asian layouts have a lower expected cycle-time than the European layout. The cycle-time estimates were statistically validated via simulation using data from a terminal in the port in Busan, South Korea.

In general, the literature seems to focus on studying systems with ASCs and the relation with the block layout design. In general, designing blocks for ASCs involves finding a balance between crane speed and block length, width, and height. Long blocks imply long cycle times in the European layout. Wide blocks typically imply slower cranes, while high blocks imply more reshuffles. On the other hand, short, narrow, and small blocks imply less storage capacity and higher investment cost.

4.2. Yard layout design

Basically, literature on layout design can be divided in two streams, namely (1) overall yard layout design, including determining the number of blocks; and (2) block yard layout design. In general, the literature focuses on design methods for analyzing the relation between the layout and container terminal performance.

Within the *overall yard layout design problem*, two main decisions can be noticed, namely the relative positioning of blocks in the yard and the required number of blocks. Wiese, Suhl, and Kliewer (2009) presents a Mixed Integer Program (MIP) to find a layout that minimizes the total rectilinear travel distance between the quay area, storage blocks, and yard gate. A high-level simulation was used to show that the MIP outperforms man-made layouts slightly in terms of average quay crane moves per hour. Wiese, Suhl, and Kliewer (2010) propose an IP for an optimal rectangular Asian layout by minimizing the total truck traveling and gantry crane reshuffling costs. The decision is to determine the number and location of driving lanes assuming random storage and retrieval requests, single-cycle handling, and uniform usage of the storage area. For the rectangular storage yard case, the authors conclude that the proposed heuristic is within 1.5% of the optimal solution and finds the optimal solution in 38% of the realistic instances tested. For non-rectangular storage yards the model is adapted to a non-linear model and a variable neighborhood descent heuristic is proposed.

Several papers propose methods to *derive the number of blocks required in a yard*. Kim, Park, and Jin (2008) study parallel and perpendicular layouts served by yard trucks and a fixed number of RMGCs that are able to travel between blocks. The physical measures of both the yard and block are known. The objective is to minimize the weighted cost of yard trucks (from berths and gate) and expected reshuffling cost. Under the similar assumptions as described for Wiese et al. (2010) including that the gate is required to be in the center of a side of the yard, and using data from a container terminal in South Korea, it was found that the parallel layout outperformed in this setting the perpendicular layout. Chu and Huang (2005) derive a formula to estimate the number of bays in container terminals with straddle carriers, RTGCs, and RMGCs. A case study on container terminals in the Taiwan ports is presented to determine the best yard layout for each type of MHE considered. It is concluded that for this specific port, SCs perform well for one-berth terminals, yet are outperformed by gantry cranes for larger terminals.

Lee and Kim (2010b) study the *block layout design problem* by proposing several models to optimizing block size dedicated to either import or export containers for Asian and European layouts. Four optimization models are proposed; (1) minimize the weighted expected YC cycle-time (Lee & Kim, 2010a) with the minimum storage capacity; (2) minimize the weighted expected truck waiting times subject to minimum storage capacity; (3) maximizing the storage capacity subject to the maximum GC cycle-time; and (4) maximizing storage capacity subject to maximum truck waiting time. Their results show that the optimal number of block-bays (block-rows) for the Asian layout was larger (smaller) than for the European layout.

Simulation and analytical techniques are used to test the impact of the yard and block layout decisions on specific performance measures in the terminal. Chen, Fu, Lim, and Rodrigues (2004) focus on minimizing the utilized yard space while satisfying space requirements. The problem is transformed into a directed acyclic graph and used in several metaheuristics. A Genetic Algorithm (GA)-based heuristic outperformed all other heuristics, finding results within 8% of a simple lower bound in most cases. Lim and Xu (2006) propose a critical-shaking neighborhood search to overcome the long runtimes and outperform the results of Chen et al. (2004). Petering (2009) uses simulation to determine the effect of storage block width on the average quay crane work rate (GCR) on a transshipment container terminal with an Asian layout and blocks dedicated to groups. For each simulation run, the total yard storage capacity, number of gantry cranes (GCs) and Yard Trucks (YTs) deployed, and GC handling speeds are considered constant. The simulation uses control policies of Petering and Murty (2009). It is concluded that: (1) GCR is concave with respect to the block width; (2) GCR improves as the shape of the terminal becomes more square; and (3) the optimal block width decreases when more gantry cranes are deployed.

Kemme (2012) studies the equipment selection and layout problem in relation by performing exhaustive numerical experiments in analyzing four different configurations for RMGCs and 385 different layouts. Regression analyses are performed on simulation results to rank equipment and to study the effect of stack height and width in relation to the type of RMGC used. It is shown that there is a relation between the configuration of the yard, the type of equipment used and the resulting waiting times for transfer vehicles responsible for the transport operations.

The results presented in this section are very dependent on the modeling assumptions made, cases studied and the quality of the routing method used when comparing the MHE. Making unfair assumptions or using suboptimal solution methods could lead to biased conclusions. Also, other aspects of the MHE, such as its costs, flexibility and scalability, needs to be considered when making the MHE decision. In general, based on the literature and on the authors' experience, straddle carriers are a good storage yard MHE for small to medium size terminals. For large terminals, straddle carrier layouts will be affected by congestion and storage capacity. For large transshipment terminals, Asian layouts are better suited. On the other hand, for large terminals that handle import/export containers the European layout is arguably better suited. In terms of growing capacity in an automated storage yard, a logical strategy would be to use single YCs until no additional blocks may be added. At that point, either passing or non-passing cranes should be implemented, depending on the relative speed of the crane on each configuration.

5. Storage space assignment

The storage space assignment deals with finding the best allocation of containers to storage spaces. A good storage space assignment is one that reduces the storage yard operations cycle time (i.e., the time to store, retrieve, and reshuffle). The fitness of a storage space assignment depends on the availability and quality of the arrival and departure time information for the import, export and transshipped containers handled. Literature usually specifies the type of containers considered in their studies.

Both hierarchical and integrated solution approaches are discussed for storage space assignment decision making. Typically, in a hierarchical approach, a block will be selected first, followed by the specific storage location within that block. The level of detail used in methods varies from considering groups of containers up to studying all relevant details as weight, size, and refrigerated per individual container.

In reviewing, we arbitrarily divide literature into five main categories: (1) assignment of individual containers; (2) assignment of groups of containers; (3) comparison of storage space assignment rules and sensitivity analysis; (4) housekeeping; (5) storage space assignment in relation to other yard processes. Literature for each of these aspects is described in this section.

5.1. Storage space assignment of individual containers

Hierarchical approaches are presented in Guldogan (2010) and Park, Choe, Kim, and Ryu (2011) to first assign containers to blocks and secondly to specific locations within the selected block. At the first level, Guldogan (2010) considers an integrated policy that takes into account the work balance, number of trucks traveling and the travel distances, while for the second level a segregation strategy is proposed that clusters containers according to their departure dates. Park et al. (2011) first select blocks to balance the ASCs' workload, and secondly, select the specific storage location based on a weighted function of space and ASC utilization. The search for improved weight combinations is performed real-time, while in operation. Chen and Lu (2012) aim to avoid rehandles in their hierarchical approach to assign outbound containers. Authors all use different sets of data (Port of Izmir by Guldogan (2010), and port of Shanghai by Chen and Lu (2012)), which makes comparisons difficult. Ng, Mak, and Li (2010) present an IP formulation and an iterative constructive heuristic for the problem with export containers on ports with cyclical calling patterns.

Specific container characteristics are addressed in the methods proposed by Fu, Li, Lim, and Rodrigues (2007) and Bazzazi, Safaei, and Javadian (2009). Fu et al. (2007) propose several metaheuristics including Tabu Search (TS), Squeaky Wheel Optimization (SWO), Simulated Annealing (SA), and Genetic Algorithm (GA) for the problem for containers with different sizes. Bazzazi et al.

(2009) consider different types of containers (e.g., different sizes, empty containers, refrigerated) while using data of the Shahid Rajaei terminal in Iran. An IP formulation and GA for the problem are presented to minimize the weighted work balance among blocks for the vessel unloading and retrieval operation. The best heuristics are around 5% from the optimum.

5.2. Storage space assignment of groups of containers

Several authors propose methods to assign groups of containers to storage locations, where groups are, for example, based on the destination vessel. Nishimura, Imai, Janssens, and Papadimitriou (2009) give a MIP, the corresponding Lagrangian relaxation and a heuristic to minimize the weighted total container handling time. The heuristic's performance is assessed for variations in type of berth (traditional or indented), the transfer vehicle travel times, and unloading times. An SA-based heuristic for this problem is proposed by Huang and Ren (2011) that requires enumerating all possible assignment permutations for the three container groups of export containers. The performance of the heuristic is not compared to existing storage policies.

Woo and Kim (2011) propose four rules to determine the amount of blocks to allocate to groups of export containers. The square root of arrival rate (SRAR) rule, where empty blocks are reserved proportional to the square root of the arrival rate of containers of the respective group, was selected as the best performing rule by means of a simulation study. This rule was developed given the insights from an analytical derivation of the minimum number of blocks to dedicate to a container group, which the authors assert to be directly proportional to the loading time of a vessel. The SRAR rule was used to estimate the space requirement for export containers using real-world data from a terminal in Pusan, South Korea. It was concluded that the estimates from the model are comparable to those from the terminal. Jeong, Kim, Woo, and Seo (2012) define a method to decide for each block how many import containers will be stored there.

5.3. Comparison of storage space assignment rules and sensitivity analysis

Both simulation and analytical approaches are used to compare different assignment policies and to test the impact of sensitivity to, for example, available information. Dekker, Voogd, and Van Asperen (2006) use simulation to compare two storage space assignment policies. The random stacking policy is shown to be outperformed by their category stacking policy, which stores containers of the same group together. Several intuitive online stacking policies are presented in Borgman, Van Asperen, and Dekker (2010) and subsequently used to show that having departure time information helps create better storage space assignments. An interesting strategy is proposed where container storage space assignment is based the containers' expected duration of stay. It is found that for large blocks a grouping strategy performs similar to having perfect departure time information per container.

Ku, Lee, Chew, and Tan (2010) compare several storage space assignment strategies for RMGCs by solving MIP models, assuming no repositioning. By relaxing some constraints in the mathematical formulation it is found that, as expected, a non-dedicated strategy (i.e., containers are not grouped by departing vessel) yields a better gantry crane utilization. Later, Ku, Chew, Lee, and Tan (2012) studied weekly templates that are easy to change based on information such as vessel arrival times. A two-stage approach is suggested. The first stage seeks to minimize the cost of the worst case scenario before uncertainty is revealed, whereas the second stage optimizes after uncertainty is revealed. Several heuristics for each stage are proposed, based on solving different modifications of the formulation from Ku et al. (2010). Several heuristic approaches are empirically compared by combining different strategies for each stage.

5.4. Housekeeping

Some shipping companies include in the contract a preferred storage location for loading and unloading. Their objective is to ensure that the time to unload and load their vessels is reduced by minimizing the expected transfer vehicles' travel time from the berth to the storage yard. These contractual agreements typically force some reshuffling of containers either to clear the preferred unloading area or to have the containers in the preferred loading area. This storage yard reorganization strategy is commonly known in the container terminal literature as *housekeeping*. The literature on selecting the storage space assignment under this situation typically seeks to minimize the number of reshuffles necessary.

Cordeau, Gaudioso, Laporte, and Moccia (2007) seek to assign containers to storage spaces to minimize the housekeeping effort for the Gioia Tauro container port in Italy. Two linear MIP models for the problem are presented. Given the complexity of the problem, a memetic heuristic (i.e., a combination of GA and TS) is proposed which temporarily allows infeasible solutions that are made feasible at a later stage. Experimental results show that the proposed heuristic found the optimal solution in all small instances tested, and outperformed the truncated B&B from CPLEX for the two models.

5.5. Storage space assignment in relation to other yard processes

Most authors address only a single operational decision problem, however, from a practical point of view there exist many interactions with other operational aspects. Here we will highlight papers that address more integrated decision making. Murty, Liu, Wan, and Linn (2005) and Murty, Wan, et al. (2005) design a decision support system (DSS) for overall decision making (e.g., internal transportation, allocating storage space, deploying gantry cranes to blocks, and setting appointment times for external trucks) at the container terminals in the Port of Hong Kong, China. The storage space assignment is done by solving a LP to balance the *fill ratio* of the blocks in order to minimize transfer vehicles congestion. A best-fit type algorithm is proposed inspired by the bin packing problem. Murty (2007) proposes a storage space assignment policy for a terminal using a consignment strategy. The policy is an adaptation of the best fit on-line heuristic for the bin packing problem.

Lee, Chew, Tan, and Han (2006) study storage space assignment to minimize the total number of gantry crane shifts required to handle all the workload. An assignment of container groups to sets of blocks is assumed to be determined a priori, and constraints on workload and proximity are imposed to reduce traffic congestion. A MIP, a lower bound, and two heuristics are proposed. The lower bound and the heuristics are based on sequentially solving the problem for each shift individually. Han, Lee, Chew, and Tan (2008) expand upon Lee et al. (2006) to incorporate the assignment of container groups to sets of blocks in the decision making. Experiments based on data generated considering data patterns from a high-traffic terminal were performed by varying the storage yard utilization. It was found that the proposed heuristic finds an optimal solution in most of the scenarios considered. Jiang, Lee, Chew, Han, and Tan (2012) extend this line of work by including space utilization as a goal. Laik and Hadjiconstantinou (2008) simultaneously address the storage space assignment problem under a consignment strategy and the gantry crane dispatching problem. The objective is to minimize the total handling and storage cost over a planning horizon, and to balance the workload between blocks.

Lee, Jin, and Chen (2012a) integrate the decisions of determining the schedule of feeder vessels and the storage location for transshipment containers. The problem is formulated as a MIP and solved heuristically using a Lagrangean relaxation-based heuristic. Their objective is to minimize a weighted combination of the total travel distance between quay and yard, and the workload imbalance between shifts. The berthing location for the vessels is assumed known.

In general, container terminals should use whatever information regarding storage and retrieval times (or sequence) is available when selecting a storage location, even under imperfect information. Unfortunately, in practice, it is not unusual that a container is retrieved at a terminal without even knowing where it is destined. This situation results in loss of productivity at the storage yard.

6. MHE dispatching and routing

In this section we study both dispatching and routing literature for different types of equipment used in different kind of yard layouts. In the dispatching problem containers are assigned to MHE, i.e., it is determined which piece of equipment will execute which jobs. In the routing problem, the sequence of jobs is determined per piece of equipment. Together, the dispatching and routing problems form the container yard's equivalent to the Vehicle Routing Problem. In general, jobs for yard MHE need to be sequenced in a way that minimizes the total transfer vehicles' waiting times, which as a result contributes to minimizing the vessel operation times. On the other hand, if the storage yard operations are decoupled (asynchronous) from the transfer operations, the objective of the storage yard operations could be to maximize throughput or minimize the maximum completion time.

With regard to the routing problem, the type of MHE to a large extent determines the complexity of the problem. We start with the single gantry crane and straddle carrier routing problems operating in a single block. Secondly, we discuss multiple (automated) cranes that operate in the same block. Finally, we focus on multiple gantry cranes that operate in different blocks. All configurations are studied in both Asian and European yard layouts. Fig. 6 provides an overview of the line of research in this field and pictures which papers study which topics. We have added several papers that were published before 2004 and previously discussed in Vis and De Koster (2003) to give the overall overview and to clarify where gaps in literature emerge. We conclude that before 2004 mainly routing of straddle carriers was discussed. Lately, we notice an increased number of publications studying routing of (automated) RMGCs.

6.1. Dispatching problem

The *dispatching problem* is studied by Petering, Wu, Li, Goh, and De Souza (2009) for RTGCs operating without cross gantrying in an Asian layout. Simulation is used to assess the twelve proposed GC dispatching rules by using the long-run average quay crane productivity. In a similar study, Petering and Murty (2009) compare two RTGC deployment strategies as well as the effect of block length on the long-run average quay crane productivity. The first RTGC deployment strategy restricts the minimum and maximum number of GCs in a block, while the second strategy allows free inter-block movement. It is concluded that the deployment policy that restricts the number of GCs in a block outperforms the free inter-block movement strategy. Also, it is found that long-run average quay crane productivity is concave with respect to the block length, for the four container terminals considered.

6.2. Routing problem for a single crane

Several authors discuss the *routing problem of a single gantry crane or straddle carrier*. For Asian configurations it is typical that the specific loading sequence of QCs is followed at the yard and that yard bays are dedicated to container groups. Hence, the problem is typically to determine the bay sequence and how many containers will be retrieved from each bay. Clearly, if each container group is requested at once or if each container from a particular group is in the same bay, the problem becomes simple. For the European configuration, the GC has to travel for each request to one of the ends of the block. Consequently, the sequence in which requests are retrieved is typically a decision to minimize the total GC travel distance.

Ng and Mak (2005a, 2005b) propose methods to minimize the container waiting times, given deterministic transfer vehicle arrival times and constant container retrieval times. Ng and Mak (2005a) focus on the development of the upper bound, while Ng and Mak (2005b) propose a B&B algorithm based on the lower and upper bounds. Kumar and Omkar (2008) present an IP model which turns out to be the same model of Ng and Mak (2005a,

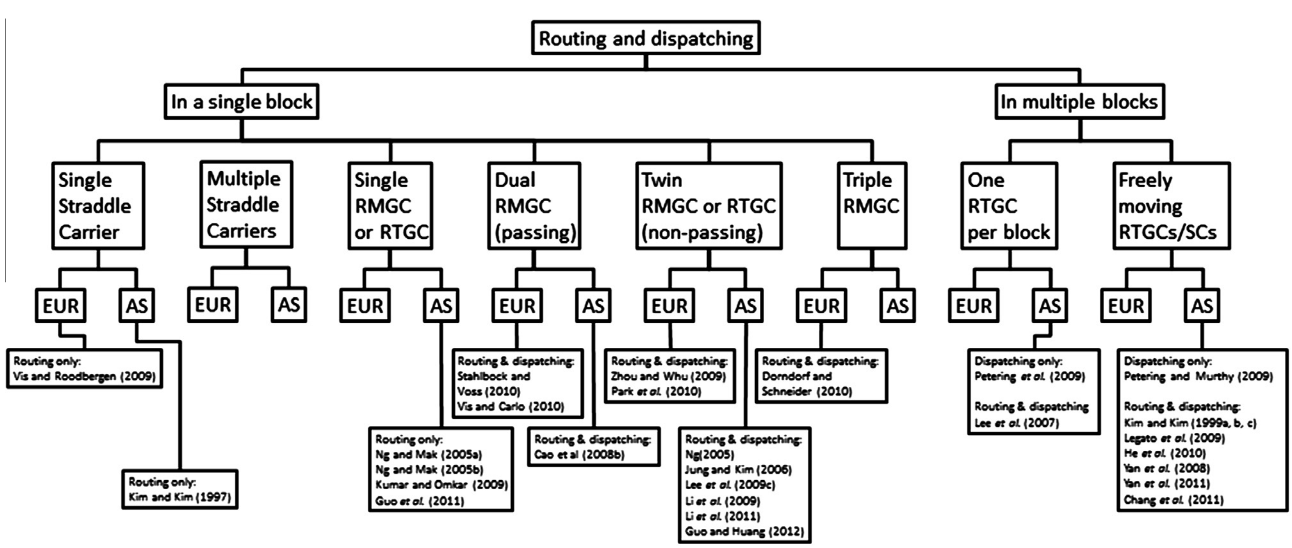

Fig. 6. Overview of research MHE dispatching and job sequencing. (See above-mentioned references for further information.)

2005b). It is claimed, without results, that their heuristic finds better schedules than the heuristic in Ng and Mak (2005a). The deterministic single-RTGC routing problem is addressed in Guo, Huang, Hsu, and Low (2011) for a terminal with Asian layout to minimize the average transfer vehicle delay. A best-first-B&B algorithm is proposed in combination with a Recursive Backtracking strategy. It is concluded that the algorithms perform well even when predicted ready times are not accurate.

Vis and Roodbergen (2009) propose a polynomial-time algorithm to route a *single straddle carrier* used exclusively in the yard to serve multiple rows. The objective is to minimize the makespan to serve a set of storages and retrievals. The problem is shown to be a special case of the Rural Postman Problem that can be reformulated as an asymmetric Steiner Traveling Salesman Problem. The algorithm solves a bi-partite network Linear Assignment Problem (LAP) to match the storage and retrieval requests in a row. Then, dynamic programming is used to effectively combine all rows. The problem is solved assuming the SC is able to move bi-directionally or unidirectional. This algorithm may be used for GC scheduling as in Vis (2006) and Vis and Carlo (2010).

6.3. Routing and dispatching of dual passing RMGCs

Dual passing RMGCs configurations in Asian layouts are studied by Cao, Lee, and Meng (2008). GC interference is considered by not allowing both cranes to retrieve a container from the same bay and not allowing the smaller RMGC to pass a particular bay while the larger RMGC is retrieving a container from that bay. An IP formulation for the problem is presented to minimize the makespan. Furthermore, a greedy heuristic, SA with the encoding scheme of Lee, Cao, and Meng (2007), and a combined heuristic are proposed. The combined heuristic uses the solution of the greedy heuristic as an initial solution for the SA. The results suggest that given the weak performance of the selected SA scheme, the combined heuristic has room for improvement.

Online heuristics for *dual passing RMGCs in a European layout* are proposed by Stahlbock and Voß (2010) considering reshuffling. The main objectives are to minimize the total weighted earliness and lateness, as well as empty travel. Three priority rule-based procedures that restrict the problem size and a SA-based heuristic are presented. A simulation study based on a container terminal in Hamburg, Germany was used to compare the solution methods. It is concluded that SA outperformed the priority rule-based heuristics for high workload instances. Vis and Carlo (2010) study the passing ASC routing problem for both sea and landside storage and retrieval requests in a European configuration. An SA method searches for the ASC dispatching, using the optimal routing of Vis and Roodbergen (2009) as input. Then, the resulting candidate solution is evaluated to incorporate the interference delays. Experimental results show that the SA is within 2% of the lower bound in large instances of the problem. Although it is not explicitly stated in the paper, the experimental results shown do include the delays caused by the fact that the two ASCs may not operate on the same bay at the same time and that the smaller crane cannot pass through a bay if the larger crane is operating on it. Although it could be easily incorporated into the SA, reshuffling was not considered in the experimental results.

6.4. Routing and dispatching of twin non-passing GCs

For the *Asian configuration*, Ng (2005) focuses on minimizing the total completion time to serve all (directly accessible) requests in a single block, and presents an IP model, a lower bound and a heuristic. The heuristic decomposes the problem into multiple single-gantry crane scheduling problems with iterative re-assignment options. Experimental results show that the proposed heuristic is on average within 7.3% of the lower bound. The approach of Ng (2005) is used by Sharif and Huynh (2012) in comparing decentralized and centralized scheduling approaches. Jung and Kim (2006) propose a method to determine the number of containers to be retrieved from each bay and the sequence for each GC in order to serve a list of retrieval requests with constant retrieval times in a way that minimizes the makespan of the pre-specified loading plan of the GC. GA and SA are used to solve the problem. Lee, Cao, Chen, and Cao (2009) assume that multiple identical GCs with constant handling times operate in a block and that the GCs are limited to travel only within specific areas of the block.

Li, Wu, Petering, Goh, and De Souza (2009) study twin GCs routing and dispatching with ready times and space constraints on an Asian layout. Only requests from the seaside are considered. It is assumed that GC handling times is constant and that transfer vehicles are always available. A MIP formulation and heuristic to minimize the weighted total retrieval earliness and transfer vehicles delays are proposed. It is claimed that the heuristic outperforms the one in Ng (2005), even though it has additional constraints such as a GC safety distances. A rolling-horizon approach further reduced the runtimes at the expense of a small decrease on the average solution quality. An extension is presented in Li et al. (2012) by formulating the problem as a more efficient continuous-time MIP and adding operational constraints to further reduce the solution space.

A hierarchical scheme for dispatching the GCs by Guo and Huang (2012) aims at minimizing the average waiting time for transfer vehicles. The first level distributes GCs among different rows, and the second level dispatches GCs in a row based on a time and space partition. The third level determines the routing of the GCs. Instead of partitioning based on the number of jobs, the space partitioning algorithm considers a pool of candidate partitioning solutions through a combination of simulation and optimization considering the effects on the third level. Experimental results show that one of the proposed algorithms outperforms the partitioning scheme of Ng (2005). It is also concluded that balancing workload simply by the number of jobs does not work well.

With respect to *twin GCs routing and dispatching in a single block* in the *European configuration*, Zhou and Wu (2009) propose an approach to find the sequence and exchange point for each request given specific due date requirements. It is assumed that bays are dedicated to container groups, that cranes travel at different speeds when empty or full, and that all containers must be handled by both cranes sequentially by using an exchange point. The paper presents necessary and sufficient conditions to determine if all requests can be served without violating any due dates. Based on these conditions, optimal algorithms are provided to minimize the maximum tardiness, the number of tardy jobs, makespan, and weighted completion time. Park, Choe, Ok, and Ryu (2010) focus on online scheduling of twin ASCs in a European configuration. Container reshuffling is considered by treating these movements as independent requests that may be handled by either crane. The look-ahead heuristic encodes a solution by specifying the sequence in which requests will be served, the ASC dispatching to each request, and the priority in case of interference. Experimental results show that, as expected, the look-ahead heuristic outperforms the alternative greedy heuristic.

6.5. Routing and dispatching of triple RMGC

The problem for triple RMGC is even harder than the previous problems since now care has to be taken of dispatching among three gantry cranes, as well as take any interference between them into account. Dorndorf and Schneider (2010) focus on *scheduling triple-ASCs in a European layout* and consider the GC interference that occurs between the two non-passing ASCs and when the larger ASC lowers its spreader to serve a request. Given a set of storage, retrieval, and reshuffling requests with time windows from the seaside and landside, the objective is to maximize the productivity of the triple-ASC system while preventing delays at both ends of the block. The system studied assumes that the two non-passing ASCs may collaborate in an asynchronous manner. In other words, containers may be handled by both non-passing ASCs by placing containers in an exchange zone. However, it is assumed that the non-passing ASCs will not place and retrieve a container in the exchange zone in the same planning period.

The problem is solved dynamically by optimizing the dispatching and sequencing of requests whenever a request is completed or a new one arrives. A beam-search approach is used for the ASC dispatching. Given the ASC dispatching, B&B is used to find the optimal job sequencing, considering ASC interference. The heuristic is compared to using earliest due date, nearest neighbor and a set of heuristic rules used by the terminal operator. It is concluded that the proposed heuristic is able to increase the productivity of a block by an average of 21.2% over the other heuristics considered without affecting the on-time performance. During load peak time, the performance of the seaside improved by an average of 35.7%.

6.6. Multiple GCs operating in different blocks

For the situation with multiple GCs and multiple blocks, jobs are to be assigned to the available GCs, where there is no a priori assumption on which GC(s) operate(s) in which block(s). The approach may be integrated, or multi-stage with first an assignment of GCs to blocks and secondly an assignment of jobs to the GCs. Interference between GCs, and additional time for block changing by the GCs may need to be considered.

Given a pre-specified loading plan and blocks dedicated to groups of containers, the problem studied by Lee et al. (2007) is a deterministic version with the objective to minimize the GC operation's makespan. A mathematical formulation for the problem and a SA-based heuristic are presented. Multiple interfering cranes with *inter-block movement* are studied by Legato, Canonaco, and Mazza (2009) in order to minimize the weighed cost of inter-block movements and activating idle GCs. A mathematical formulation is presented to determine pairs of blocks for each RMGC. It is assumed that at most one RMGC can operate on a block at the same time. A discrete event simulation is used to compare five inter-block dispatching rules: random, closest yard block, greatest priority, shortest workload, and greatest workload, with the closest yard block policy outperforming the other strategies.

He, Chang, Mi, and Yan (2010) study the GC scheduling problem to minimize the weighed number of delayed request and the inter-block GC distance during the planning horizon. The model assumes that at most two RTGCs may operate on the same block, that each GC can move at most twice between yard-blocks in the same period, that uncompleted workload is passed to the next planning period, and that blocks are dedicated to container groups. A hybrid heuristic, which uses seven heuristic rules to reduce the search space and parallel GA to solve the remaining problem, is proposed. The proposed heuristic outperforms the best-first-search heuristic of Yan, Huang, and He (2008), using data from a container terminal in Shanghai, China. Yan, Huang, Chang, and He (2011) build upon this line of work by developing a knowledge-based system for gantry crane scheduling based on experts' experience and knowledge.

The RTGC scheduling problem in an Asian layout with the objective to minimize the total request delays at the blocks is considered in Chang, Jiang, Yan, and He (2011). The study considers inter-block movements, reshuffling, and allows up to two RTGCs to operate on the same block. It is assumed that blocks are dedicated to container groups. A dynamic rolling-horizon strategy is used to solve the problem. An IP formulation for the problem is presented. However, due to the complexity of the problem, a simulation model with an embedded tree-based construction heuristic are proposed. The result from the heuristic is used as an initial solution for a GA. The dynamic rolling-horizon approach is compared to their static rolling-horizon in He et al. (2010). Experimental results show that the proposed dynamic rolling-horizon outperformed their static rolling-horizon in terms of solution quality at the expense of a small increase in solution time.

6.7. Remaining remarks on routing and dispatching

An interesting additional GC operational problem is to determine the trajectory that will be taken by a gantry crane (and its hoist) to serve requests. Huang, Liang, and Yang (2009) studies the best combination of horizontal and vertical movements for an ASC (and its hoist) to travel over several blocks of containers in a two-dimensional space. A non-linear bi-objective formulation of the problem is presented. The first objective is to minimize the sum of the weighted length and smoothness (i.e., angle changes) of the path. The second objective is to maximize the sum safety distance between the ASC hoist and the container blocks. A GA-based heuristic is proposed to solve the problem. The solution quality of the proposed heuristic was not tested.

It may be expected that future container terminals work asynchronously between the storage yard and transfer vehicles. The decoupling of these operations would not only allow for higher GC throughput, but also minimize the operating costs, including consumed energy and distance-based maintenance. Unfortunately, as automated terminals proliferate, terminal managers will become more dependent on software offered by integrated solutions providers. Hence, the implementation of these algorithms in practice will come down to the inclusion in their offerings. Furthermore, automated terminals that operate with high-throughput fixed-path MHE do not provide much flexibility for terminal managers to overcome unexpected operational situations.

7. Container reshuffling

Block stacking is used to minimize the surface required to store containers, at the expense of not having all containers available for direct retrieval. To retrieve one of the lower containers, other containers that are on top of it, may need to be relocated first. This process of *reshuffling* containers can be performed on the fly, while loading of the vessel is ongoing, or can be done before the vessel's loading operation starts.

The container reshuffling literature can be divided into four main streams, with some papers addressing more than one. (1) To prevent or to minimize reshuffling, storage locations for arriving containers can be selected considering expectations on their future retrieval sequence. (2) Joint retrieval sequencing and reshuffling to meet a loading plan and its corresponding container retrieval sequence. (3) *Pre-marshaling* is the operation that reorganizes the container stacking beforehand, such that for a known retrieval sequence no reshuffling will be required. (4) With *re-marshaling* containers are removed from their current storage locations and prepositioned in a separate area in the yard assigned to a specific vessels. Fig. 7 shows the different lines of research in this area and shows the relevant papers in each area that are discussed below.

In general, for reshuffling decisions it is assumed that the specific retrieval sequence of containers is known in advance. Unless otherwise stated, the reshuffling publications assume that reshuffling is limited to containers in the same block or bay and that reshuffling is only performed when required to retrieve a particular container. Given the operational cost of gantry cranes and the

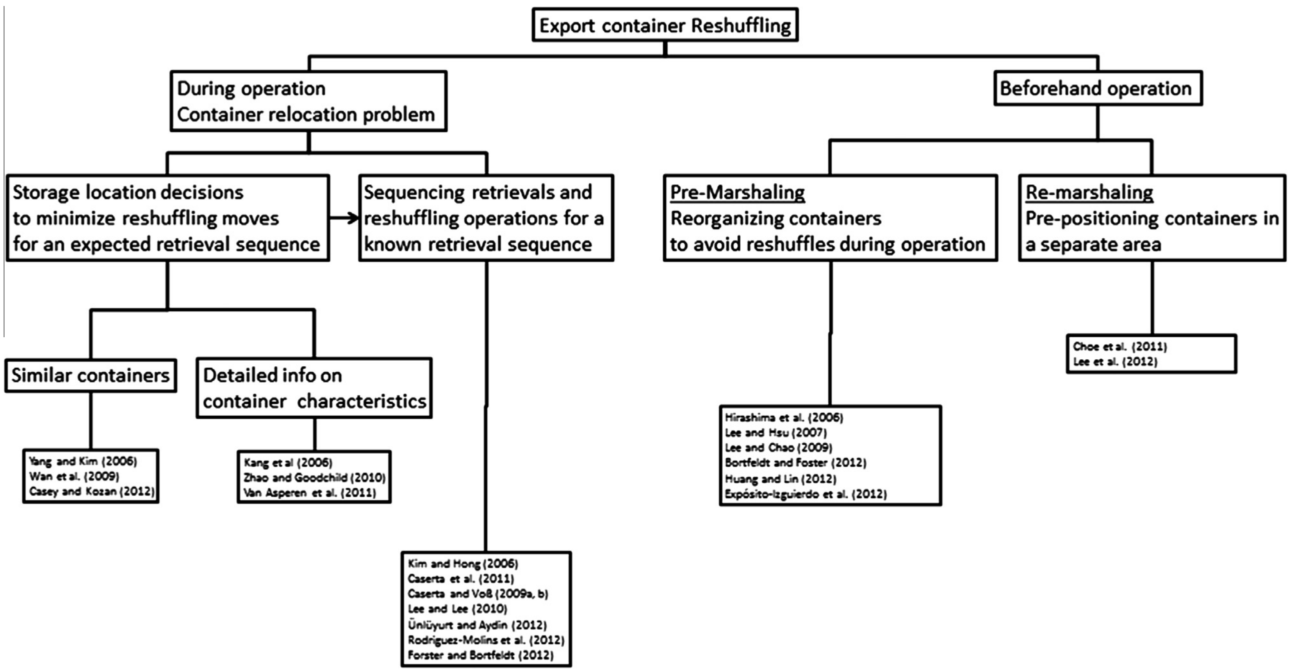

Fig. 7. Overview of research in container reshuffling.

imperfect nature of the information, containers are typically not reshuffled until required.

7.1. Selecting storage locations for arriving containers

The problem of selecting storage locations is studied Yang and Kim (2006) who propose a simple IP formulation and a DP and GA-based heuristic for the static version of the problem under the assumption that containers are classified into groups. The dynamic minimum space waste rule, which assigns a space waste index to blocks based on the expected waste of storage space and storage time, was found to outperform the other two heuristics. Wan, Liu, and Tsai (2009) propose an IP formulation that determines the new location of a reshuffled container by minimizing the number of reshuffles required to empty a storage bay. The IP model is used as part of an IP-based heuristic which decomposes the problem into a series of reduced (size) problems by considering a subset of containers to be retrieved. The sub-problems are solved sequentially, similar to a rolling-horizon strategy. The IP-based heuristic and three existing heuristics: Lowest Slot (LS) heuristic (i.e., select the open storage location in the lowest tier), the Reshuffling Index (RI) heuristic of Murty, Liu, et al. (2005), and the Expected Number of Additional Relocation (ENAR) heuristic from Kim and Hong (2006) all perform close to optimal in low density instances; for medium and high densities the extended-RI and extended-ENAR perform very well. The IP-heuristic outperformed all heuristics in the static case, although it was not as dominant as in the dynamic version of the problem. Casey and Kozan (2012) assign storage locations to incoming and reshuffled containers served by a straddle carrier. A mathematical model that minimizes the total time spent by the straddle carriers in the yard is proposed. Four constructive heuristics are proposed. It is concluded that a modification (on the sequence in which rules are applied) of the method from Caserta, Schwarze, and Voß (2008) performed best. Without providing specific details, the authors claim that with a slight modification their solution method outperformed the one in Lee and Lee (2010). Both Caserta et al. (2008) and Lee and Lee (2010) address the second reshuffling decision and are hence discussed later.

Several authors study the impact of having more detailed information in tackling the first reshuffling decision. Kang, Ryu, and Kim (2006) consider container storage strategies for same-weight-group stacking of export containers underweight-information uncertainty. A formula to estimate the number of re-handlings under uncertain weight information and some ordering constraints is derived. A stacking strategy based on SA, which takes into account the probability distribution of the true weight group given the estimated weight group, is developed and shown to reduce the number of re-handles compared to the traditional strategy. Zhao and Goodchild (2010) study the effect of considering container departure time information to minimize the number of reshuffles and intra-bay gantry crane travel distances for import containers for three different heuristics by means of simulation. Similar to the results in Borgman et al. (2010), Zhao and Goodchild (2010) conclude that a complete arrival sequence is not required to substantially reduce the number of reshuffles. As expected, the benefit in terms of the number of reshuffles is reported to increase with the storage capacity of the bay. Van Asperen, Borgman, Dekker (2013) uses the models of Dekker et al. (2006) and Borgman et al. (2010) to evaluate the impact of truck departure time information on the time to retrieve a container, the ASC workload, the number of reshuffles required. Experimental results show that truck announcement information has an impact on the exit time of containers. However, announcements made with too much anticipation could be counterproductive in their implementation as in order to keep a container unblocked more reshuffles might be incurred with newly stored containers. Truck announcement information was found particularly beneficial for environments where there is unreliable or no information.

7.2. Joint retrieval sequencing and reshuffling

Other papers focus on joint retrieval and reshuffling sequencing, though many assume an a priori given retrieval sequence and thus only focus on interfacing the reshuffles into the given retrieval sequence. Kim and Hong (2006) propose a branch-and-bound algorithm to minimize the number of reshuffles required to pick-up individual containers or groups of containers. Given the complexity of the problem, a heuristic based on the expected number of additional relocations is proposed. Two assumptions are made, (1) containers will only be relocated once, (2) random containers from other blocks will be reshuffled to the block under consideration. If the block has multiple empty locations, the (conditional) expected number of reshuffles for each empty location is computed recursively. The heuristic computes an index for each empty location on the top of a block and selects the empty slot with the minimum index. Experimental results show that the heuristic was on average 7.3% above the optimal solution in forty randomly generated experiments for the case with individual containers and 4.7% above optimal for the case with three groups of containers.

Caserta, Voß, and Sniedovich (2011) solve the same problem using a method-based neighborhood metaheuristic called *Corridor Method*. In their heuristic, the search space for the DP formulation of the problem is reduced by imposing exogenous constraints. The following constraints are used in the proposed heuristic: (1) the reshuffle a container is limited to a physical area around its current position, and (2) only bays under a certain height are considered. By imposing these exogenous constraints the problem size is significantly reduced so that the optimal solution may be computed. The proposed heuristic outperformed the ENAR from Kim and Hong (2006) in terms of the average number of reshuffles incurred. Caserta and Voß (2009a, 2009b) show variations on the corridor method. Forster and Bortfeldt (2012) propose a heuristic tree search procedure that reduces the number of rehandles compared to the previously discussed methods.

Lee and Lee (2010) focus on how to retrieve all containers from the yard area given a pre-specified retrieval sequence. Their objective is to minimize the weighted sum of the total number of reshuffles and the GC completion time. A three step improvement heuristic is proposed. The first step finds an initial feasible retrieval sequence by assuming that reshuffles are made to the closest bay with an empty slot. In the second step, the number of reshuffles in the initial sequence is reduced by repeatedly generating and solving a binary integer program, similar to Lee and Chao (2009). Then, a MIP formulation iteratively adjusts the job sequence to reduce the GC completion time without increasing the number of reshuffles. Experimental results indicate that the heuristic outperformed the heuristic in Kim and Hong (2006), in terms of the total number of reshuffles, in all 10 one-bay instances tested by an average of 47%.

A branch-and-bound approach and heuristics for the problem as presented by Kim and Hong (2006) is given in Ünlüyurt and Aydin (2012). Benchmarking results show no direct improvement over the work of Lee and Chao (2009). Rodriguez-Molins, Salido, and Barber (2012) use techniques from artificial intelligence to create a planner that both can assist in the storage space assignment and reshuffling decisions. It is shown how balancing and security constraints can be taken into account. The authors do not compare their method with any other available method.

The two reshuffling decisions are very similar as in order to solve the second reshuffling problem one must know how to solve the first problem. That is, in the second problem one picks containers according to a sequence of requests. If the requested container is available (i.e., unblocked) it is retrieved. On the other hand, if the container is unavailable (i.e., blocked), the containers above it must be reshuffled. Where to reshuffle these containers to is the same as the first reshuffling problem.

7.3. Pre-marshaling problem

A paper that focuses on the *pre-marshaling process* for export containers is Hirashima, Takeda, and Harada (2006) where a Q-Learning algorithm assuming that each container has several preferred final positions is presented. It is concluded that the number of reshuffles by the proposed heuristic is much smaller than those generated by the human operator in a real-scale problem. Lee and Hsu (2007) solve the pre-marshaling problem assuming that reshuffles may only take place within a bay. Heuristics and a very general IP formulation as a multi-commodity flow problem in a time-space network with additional constraints, for the problem are presented. Experimental results show that, although, the heuristic could be used to solve real-life problems within a bay, runtimes seem to grow quickly with problem size and planning horizon.

Lee and Chao (2009) seek a balance between the number of movements during pre-marshaling and the number of reshuffles that would be required to retrieve all containers. The heuristic first searches for good final layouts (i.e., minimize the reshuffles required) at the cost of more movements. Then, an IP is used to reduce the number of movements. Other solution perturbation strategies such as randomly emptying a block, eliminating redundant movements, and removing blocking containers are incorporated to the heuristic. The heuristic is said to work well as long as the solution perturbation strategies are included. Unfortunately, the solution quality of the heuristic is not tested.

Several authors extend the line of work of Lee and Hsu (2007) and Lee and Chao (2009). Bortfeldt and Forster (2012) present a tree search procedure using leafs to represent potential final layouts. The authors derive a lower bound for the number of moves required to reach a final layout. Benchmarking against Lee and Hsu (2007) and Lee and Chao (2009) shows that significantly better solutions can be found much quicker. Next to that, the authors present a new set of more realistic test instances. Huang and Lin (2012) propose a heuristic to study the problem as defined by Lee and Hsu (2007) and benchmark it against two small problems which show somewhat better results. No additional experiments have been performed to test the quality of the approach, which makes it hard to make more general remarks on its performance. Expósito-Izquierdo, Melián-Batista, and Moreno-Vega (2012) propose a heuristic that focuses on positioning containers with the lowest priority first. In addition, they propose an open-source generator to create instances of the pre-marshaling problem to be used for benchmarking purposes.

7.4. Re-marshaling problem

Other papers focus on *remarshaling export containers.* Choe, Park, Oh, Kang, and Ryu (2011) study the intra-block remarshaling problem considering twin ASCs by proposing a two-step SA-based heuristic. Firstly, the target slots to which containers are to be moved are identified to minimize the total number of reshuffles (during and after remarshaling). Secondly, the ASC schedule is determined in order to minimize interference between the ASCs. Lee, Jin, and Chen (2012b) propose a 2-level heuristic to solve the problem of storage space assignment and re-marshaling decisions in a multi-terminal setting by minimizing the inter-terminal transportation costs.

8. Integrated decisions

Synchronizing quay, transfer, and yard operations is of great importance to reduce vessels' turnaround times. In this section, we discuss several papers that each studies a yard decision problem in combination with another decision problem in an integrative way. For more information related to the seaside and transport operations at container terminals the reader is referred to Carlo et al. (2013a) and Carlo et al. (2013b).

Kim, Kang, and Ryu (2004) simultaneously determine the *loading sequence for a QC* and the *retrieval sequence of containers in the* *storage yard*. The objective function in a non-linear MIP includes performance metrics such as GC travel time and number of reshuffles, as well as penalties for not following some operational considerations such as priority and a QC penalty for not loading holds consecutively. An integrated heuristic using two beam search algorithms (BSAs) is proposed which determines the number and sequence of containers to retrieve from each bay, and determines the sequence of individual containers considering the operations of the GC and QC. The BSA-based heuristic is compared to a neighborhood search procedure and an ant system heuristic where the problems are solved sequentially. The BSA outperformed the ant system heuristic in terms of solution quality and time, and, it only outperformed the neighborhood search in terms of solution quality.

Froyland, Koch, Megow, Duane, and Wren (2008) study the integrated problem between the *transfer and the storage yard operations*. The problem is decomposed into sub-problems with a small planning interval. In the first phase, an IP is used to assign a 1-hour time interval for each movement to be made by the transfer vehicles. In the second phase, given the allocation of movements to time intervals, the storage location of import containers at the seaside is optimized using a set of IPs. Lastly, in the third phase, a greedy online heuristic is used to solve the gantry cranes scheduling, assigning the short term positions of containers, and the truck bays to be used for each hour. In the third phase, the storage yard is partitioned into areas to decompose the multi-gantry crane problem into single-gantry crane problems. It is claimed that in a real scenario the heuristic performed within 8% of the gantry crane optimum time, including only 0.4% of the time spent reshuffling. The solution was also optimal with respect to the maximum number of transfer vehicles required.

Kozan and Preston (2006) simultaneously solve the *storage space assignment and the transfer vehicle scheduling problem*. An iterative search algorithm that sequentially solves each subproblem is presented. The objective is to minimize the maximum GC reshuffling plus transfer vehicle travel time. Seven heuristics were proposed by combining or decomposing the problems and by using GA, TS or both to solve the problems. Experimental results based on Port of Brisbane, Australia, found that the iterative heuristic that uses GA to solve both problems outperformed the others. The solution quality of the proposed heuristics was not compared to the optimal solution for the problem.

Lee, Cao, Shi, and Chen (2009) derive a MIP to integrate the deterministic storage space assignment on a block level with *the transfer vehicle scheduling problem* for import containers. Due to the complexity a GA and greedy heuristic are proposed. Based on computational experiments on small-size problem instances, it is concluded that the GA outperforms the greedy heuristic. Given enough GA-generations, the GA was able to find the optimal solution in 9 of the 10 small instances. In larger instances the GA outperformed the greedy heuristic at the expense of much larger runtimes.

Lee, Cao, and Shi (2009) propose a MIP to integrate the *storage space assignment problem* and *the transfer vehicle scheduling problem* considering vessel loading and unloading. A hybrid insertion algorithm-based heuristic (HIA) iteratively solves a storage space assignment problem as a sub-problem using an auction algorithm. The heuristic found solutions between 3% and 17.35% from optimal in small problem instances (average 10.27% error).

Cao, Shi, and Lee (2008) integrate the *transfer vehicle dispatching with the storage space assignment on a block level* to minimize the maximum completion time of the unloading operation. It is assumed that the quay crane schedule is known and as a result ready times for vehicles are known as well. Further, the travel time and gantry crane storage time are assumed deterministic. A mixed integer programming formulation, a Genetic Algorithm-based heuristic (GA), and a greedy heuristic are proposed. It is concluded that the greedy heuristic outperformed the GA.

Cao, Lee, Chen, and Shi (2010) integrate *the transfer vehicle and gantry crane scheduling problems* for the loading operation as a two-stage flexible flow shop problem with the objective to minimize the makespan. All operational times are assumed deterministic and there are no precedence constraints. The authors formulate a mixed integer program and two solution methods based on Benders' decomposition.

Soriguera, Espinet, and Robuste (2007) use simulation to study the *storage space assignment and dispatching strategies for straddle carriers*, which are used as transport and storage MHE. The dispatching of SCs in the simulation is performed by solving a MIP to minimize the SC empty travel time and number of reshuffles. Three different storage policies are considered. Experimental results indicate that dividing the storage yard into import and export areas can increase the productivity for particular operations. The preferred storage strategy when operating the straddle carrier in single-cycle was to store import container in the yard spaces closest to the quay area, and the export containers on the spaces closest to the landside. If the straddle carriers are assigned to more than one vessel, then a scattered location strategy is preferred. It is claimed that the number of reshuffles can be reduced by 50% and the number of required straddle carriers by 25% compared to a random selection method.

In general, we note that the integrated problems are modeled separately in stages and assuming deterministic settings. On one hand, the assumption of deterministic operational times could jeopardize the practicality of the solutions. On the other hand, the assumption allows researchers to solve larger instances of the problem. We suggest a compromise by assuming that the operational times are deterministic, but different for each container. Unloading and loading times at vessels and ships will depend on the exact storage location and vehicle travel times might be estimated with worst-case route lengths.

9. Future yard operations – challenging the paradigm

Up to this point, this paper has focused on understanding the current storage yard operations, including the latest trends and developments. This information is invaluable for narrowing the gap between theory and practice. However, this approach assumes that the current paradigm will continue to hold in the future. In this section we take a different approach by envisioning possibilities for the container terminal of the future from an Industrial Engineering and Operational Excellence perspective.

In our approach, we intend to challenge the current container terminals' operations paradigms by identifying opportunities for improvement and borrowing best practices from manufacturing, material handling, and warehousing. In general, we will identify opportunities and propose realistic solutions that consider, but are not limited by, the cost of implementation. The ideas proposed in this section are not claimed to be unique or brand new, but are intended to challenge container terminals and material handling equipment designers, as well as researchers. By examining today's storage yard operations, particularly using gantry cranes, one can quickly identify the following paradigms:

P1. The quay and yard are located at the same height (which is closely related to the quay crane concept with a second trolley as implemented in the Euromax terminal, see Euromax, 2013).

P2. On the storage yard, containers remain static and the gantry cranes move.

P3. Storage yards should be organized into rectangular blocks.

Table A.1.
Classification papers on storage yard operations in scientific journals between 2004 and 2012.

Paper	Decision Problems							Yard Layout				MHE Characteristics								Temporal					Unc.	Performance Metric						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Bazzazi et al. (2009)	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	1
Borgman et al. (2010)	0	1	0	0	0	0	0	0	1	1	0	1	0	0	1	1	0	0	0	0	0	1	1	0	0	1	0	1	0	1	1	0
Bortfeldt and Forster (2012)	0	0	0	0	0	1	0	1	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Cao, Shi, et al. (2008)	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Cao, Lee, et al. (2008)	0	0	1	0	0	0	0	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Cao et al. (2010)	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Caserta et al. (2011)	0	0	0	0	0	1	0	–	–	1	0/1	–	0	–	–	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Casey and Kozan (2012)	0	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	1
Chang et al. (2011)	0	0	1	0	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Chen and Lu (2012)	0	1	0	0	0	0	0	1	0	1	0/1	0	0	1	0	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0
Chen et al. (2004)	1	0	0	0	0	0	0	1	0	1	0	–	0	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0
Choe et al. (2011)	0	0	0	0	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Chu and Huang (2005)	1	0	0	0	1	0	0	1	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Cordeau et al. (2007)	0	1	0	0	0	0	0	1	0	0	1	–	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Dekker et al. (2006)	0	1	0	0	0	1	0	0	1	1	1	1	0	0	1	1	0	0	0	0	1	0	1	1	0	1	0	0	0	1	1	0
Dell et al. (2009)	0	0	1	0	1	1	0	0	1	1	0	1	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1	1	0	0	0	1
Dorndorf and Schneider (2010)	0	0	0	1	0	0	0	0	1	0	0	1	0	0	1	0	0	0	1	1	0	1	0	1	0	0	0	0	1	0	0	1
Expósito-Izquierdo et al. (2012)	0	0	0	0	0	1	0	–	–	1	1	1	0	–	–	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Forster and Bortfeldt (2012)	0	0	0	0	0	1	0	–	–	1	0	–	0	–	–	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Froyland et al. (2008)	0	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	0	1	0	1	0	1	0	0	0	0	0	1	1	0	1	1
Fu et al. (2007)	0	1	0	0	0	0	0	–	–	1	0	–	0	–	–	1	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0
Guldogan (2010)	0	1	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1
Guo and Huang (2012)	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	1	0	1	0	1	0	0	0	0	1	0	0	0
Guo et al. (2011)	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Han et al. (2008)	0	1	1	1	0	0	0	1	0	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
He et al. (2010)	0	0	1	0	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1
Hirashima et al. (2006)	0	0	0	0	0	1	0	1	0	1	0	–	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Huang and Lin (2012)	0	0	0	0	0	1	0	–	–	1	1	1	0	–	–	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Huang and Ren (2011)	0	1	0	0	0	0	0	–	–	1	1	1	0	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
Huang et al. (2009)	0	0	0	0	0	0	0	–	–	1	–	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Jeong et al. (2012)	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Jiang et al. (2012)	0	1	0	0	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Jung and Kim (2006)	0	0	1	0	0	0	0	1	0	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Kang et al. (2006)	0	1	0	0	0	0	0	–	–	1	1	–	0	–	–	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Kemme (2012)	0	0	0	0	1	0	0	0	1	1	0	1	0	0	1	1	1	1	1	0	1	0	1	1	0	0	0	0	1	0	0	0
Kim (2006a)	0	0	0	0	0	0	1	1	1	1	0/1	1	0	0	1	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
Kim and Hong (2006)	0	0	0	0	0	1	0	–	–	1	0/1	–	0	–	–	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0
Kim et al. (2004)	0	0	1	0	0	0	0	1	0	1	1	1	0	1	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1
Kim et al. (2008)	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Kozan and Preston (2006)	0	1	0	0	0	0	0	0	1	1	0	1	0	0	1	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	1
Ku et al. (2010)	0	1	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1
Ku et al. (2012)	0	1	0	0	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1
Kumar and Omkar (2008)	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Laik and Hadjiconstantinou (2008)	0	1	0	1	0	0	0	–	–	–	–	0/1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	0	1
Lee and Chao (2009)	0	0	0	0	0	1	0	1	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Lee and Hsu (2007)	0	0	0	0	0	1	0	1	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Lee and Kim (2010a)	0	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
Lee and Kim (2010b)	1	0	0	0	0	0	1	1	1	1	1	0	0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	0	1	1	1
Lee and Lee (2010)	0	0	0	0	0	1	0	–	–	1	0	–	0	–	–	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Lee et al. (2006)	0	0	1	1	0	0	0	1	0	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Lee et al. (2007)	0	0	1	0	0	0	0	1	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Lee, Cao, Shi, and Chen (2009)	0	1	0	0	0	0	0	–	–	0	0	–	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Lee, Cao, and Shi (2009)	0	1	0	0	0	0	0	–	–	0	0	–	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1

Lee, Cao, Chen, et al. (2009)	0	0	1	0	0	0	0	1	0	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Lee et al. (2012a)	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	1
Lee et al. (2012b)	0	1	0	0	0	1	0	–	–	0	1	0	0	–	–	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1
Legato et al. (2009)	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1
Li et al. (2009)	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Li et al. (2012)	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Lim and Xu (2006)	1	0	0	0	0	0	0	1	0	1	0	–	0	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0
Murty (2007)	0	1	0	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0
Murty, Liu, et al. (2005)	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Murty, Wan, et al. (2005)	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Ng (2005)	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Ng and Mak (2005a)	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Ng and Mak (2005b)	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Ng et al. (2010)	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
Nishimura et al. (2009)	0	1	0	0	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	1
Park et al. (2010)	0	0	0	1	0	0	0	0	1	1	0	1	0	0	1	0	0	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0
Park et al. (2011)	0	1	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	1	0	0	1	0	1	1	0	0	0	0	0	1	1	1
Petering (2009)	0	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	1
Petering and Murty (2009)	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	1
Petering et al. (2009)	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	1
Rodriguez-Molins et al. (2012)	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sharif and Huynh (2012)	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Soriguera et al. (2007)	0	1	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Stahlbock and Voß (2010)	0	0	1	1	0	0	0	0	1	1	0	1	0	0	1	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	1
Ünlüyurt and Aydin (2012)	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0
Van Asperen et al. (in press)	0	0	0	0	0	1	0	0	1	1	0	1	0	0	1	1	0	0	0	0	1	0	1	0	0	1	0	1	0	0	1	0
Vis (2006)	0	0	0	0	1	0	0	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Vis and Carlo (2010)	0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Vis and Roodbergen (2009)	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Wan et al. (2009)	0	0	0	0	0	1	0	–	–	1	0	–	0	–	–	1	0	0	0	1	1	1	1	1	0	1	0	0	0	0	0	0
Wiese, Suhl, et al. (2009)	0	0	0	0	0	0	1	1	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Wiese et al. (2010)	0	0	0	0	0	0	1	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Woo and Kim (2011)	1	0	0	0	0	0	0	1	0	0	1	–	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
Yan et al. (2008)	0	0	1	0	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1
Yan et al. (2011)	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Yang and Kim (2006)	0	0	0	0	0	1	0	–	–	1	1	–	0	–	–	0	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	0
Zhao and Goodchild (2010)	0	0	0	0	0	1	0	–	–	1	0	–	0	–	–	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	0
Zhou and Wu (2009)	0	0	1	0	0	0	0	0	1	0	1	1	0	0	1	0	0	1	0	0	0	1	0	0	0	0	1	0	1	0	0	0

The first paradigm currently forces QCs to raise their hoists higher than the large vessels in order to store or retrieve containers. However, if the quay itself is designed higher, less vertical travel would be required by the QC to position the container for pick-up by a vehicle. Unfortunately, raising the yard to the same level would be too expensive due to their size. Therefore, if the seaside level is raised, transfer vehicles would have to operate in a slope. However, when considering a storage yard using the European layout one notices that for each seaside pick up or deposit at the I/O the GCs has to once again lower its hoist from 5 to 6 tiers high to the ground level. An interesting opportunity would be to raise the level of the seaside I/O points so that the vertical hoist travel distance is minimal. This arrangement, at the same time, would significantly reduce the incline angle faced by the transfer vehicles to travel between a raised I/O point at the storage yard to a raised quay. A similar raised landside I/O point could also be favorable. For Asian layouts, the equivalent would be to raise the truck lane. However, for this layout, raising the truck lane includes some physical as well as safety challenges. Alternatively, if the quay is not raised, the same benefit is gained if the storage yards are be lowered (partially underground).

The second and third paradigms create many logistical challenges for container terminals. An analogous situation to having a static crane and the containers moving can be found in warehouses and distribution centers where a picker moves to access stored loads. Modern warehouses use MHE to bring the required loads to the picker. Examples of such material handling equipment are automated storage/retrieval systems, carrousels, conveyors, and Kiva systems. Interestingly, modern container terminals are focusing on improving the speed of the gantry cranes (pickers) instead of having the required containers (loads) move to the picker. Clearly, the biggest difference between warehouses and container terminals' storage yards is the weight of the loads. However, to our understanding the necessary MHE to challenge the current paradigm already exists. Interestingly, a system of well managed straddle carriers may be analogous to an autonomous containers' system.

10. Research avenues and conclusions

In this paper, we have introduced a classification scheme for storage yard operations, reviewed available literature, discussed the current trends and developments for storage yard operations and challenged the current operational paradigms by proposing innovative ideas. Our literature review shows that most papers focus on storage space assignment, MHE dispatching and routing, and reshuffling decisions. The majority of authors first present a (mixed) integer programming model to conceptualize the problem assuming deterministic parameter values. Mainly heuristic solution approaches based on meta-heuristics have been designed. Simulation is used for solving decision problems, as well as for comparing solution approaches.

We conclude that the design of a library of benchmark problems specifically for the storage yard operations would be helpful for further research in this area and to enable smoother comparison of the different methods. In the future, as container throughput increases and more automated terminals are designed, the routing and reshuffling literature is expected to grow. Also, publications addressing integrated problems within the storage yard, as well as across other areas of the terminals are expected to increase in the near future. We identify the following new research avenues (RA):

RA1. Optimize the storage yard layout for non-traditional berth layouts (e.g., indented berths).

RA2. Develop models to quantify the flexibility and scalability of straddle carriers systems.

RA3. Integrate inland ports as extended storage yards in container terminal operations.

RA4. Integrate storage space assignment and QC scheduling.

RA5. Develop new models for twin GCs in European layouts considering collaboration and interference between the cranes to further increase throughput.

RA6. Develop new models for twin GCs in European layouts where the seaside I/O consists of the last two bays so that both ASCs may serve the seaside.

RA7. Develop models for routing and dispatching of multiple (single and twin load) straddle carriers / Autostrads in the yard considering interference.

RA8. Develop models to quickly (and real-time) identify when the storage yard is the bottleneck operation.

RA9. Quantify the effect of routing ASCs under throughput and transfer vehicle delays objective functions in terms of the vessels' turnaround time when the yard operations or the quay operations alternate as bottleneck operations.

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Appendix A. Classification papers

See Table A.1.

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