Operations Research supports container handling

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Abstract

In this paper we will give an overview of the use of operations research models and methods in the design and operation of container terminals. We will describe the activities that take place at a container terminal and give an overview of the relevant decision problems, both at a strategic, tactical and operational level. For each of these problems the appropriate operations research contributions are discussed.

keywords: container logistics, operations research, ports

1 Introduction

Since its introduction in the sixties, the container has rapidly taken over the market for inter continental transport. Nowadays, big sea-going vessels transport containers between the continents, having a capacity of up to 8,000 TEU (Twenty foot Equivalent Unit) and even larger ships are foreseen. It was estimated that in the year 2000, about 220 million TEU were handled worldwide and volumes are still growing with double digits. This ongoing growth has put an enormous pressure on ports and terminal operators to increase productivity in order to handle all these containers in a fast a smooth way. Although container logistics has been a niche area in science, its societal importance has given rise to several research projects both in Europe and Asia and as a result, it is gaining more and more attention in the scientific area.

In this paper we give an overview of published material handling activities at a container terminal and we present the main contributions Operations Research has made in this respect. We base the overview on three sources, viz. publicly available papers in scientific journals, papers in professional publications, Master and PhD theses made available and our own experiences with projects on container handling within the port of Rotterdam. We refer to Chadwin et al. [7] for a basic introduction to container transportation. We do not tackle every aspect of container logistics, like positioning of empty containers, neither do we discuss terminal issues for which no

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quantitative models have been published, like multi- versus single user terminals and location selection. Very few overviews are available to date. A first attempt was made by Vis and De Koster [62].

The structure of this paper is based on following the flow of sea containers through a terminal. After a general introduction in Section 2, we start by discussing how containers are stowed in the vessel (stowage planning) in Section 3. Next, in Section 4, we discuss the berth allocation problem (the assignment of container vessels to berths) and the allocation of quay cranes for unloading and loading of the vessels. We continue with a discussion of the literature related to the transport of containers from (to) the quay cranes to (from) the stack in Section 5. After that, in Section 6, we discuss the stacking, that is, the temporary storage of containers at the terminal. Finally, we discuss the landside interface and some overall terminal studies in Section 7, followed by some conclusions in Section 8.

2 Container handling at terminals - description and problem overview

In this section, we will roughly discuss the activities that take place at a container terminal. Before doing so, we will first give a short historical overview of the developments in container transportation.

2.1 Historical developments

The invention of the container is usually attributed to Malcom McLean, who started the movement of trailers on ships (with the Sea/Land line) and rail from New York to the Gulf Coast in 1956 (see Chadwin et al. [7]). Later on, the trailer changed to containers. The container has increased port productivity enormously and in fact, the whole globalization would have been impossible without containers. Containers have also changed the appearance of harbors from pears with breakbulk cargo to long stretches of bulkheaded waterfront with many large cranes serving big container ships. The container has also allowed wages to be increased considerably and with the container ICT has made its inroad into harbors.

Container handling technology has also evolved over the years, not only in terms of type, size and capacity, but also in ways to control. In the beginning, ships were equipped with cranes to load and unload the containers themselves, or traditional shore equipment was used. However, as the container revolution went on, specialized equipment was developed, allowing for a faster handling of containers. Worthwhile mentioning is the introduction of automated equipment by the container terminal operator ECT in Rotterdam in the 1990s. They were the first to start transporting containers from the quay cranes to the stack using automated guided vehicles and stacking them using automated stacking cranes. Although it took considerable time to develop this technology, performance is now satisfactory and more terminals in Europe are following ECT in this respect. The automated equipment, however, requires a much more sophisticated control environment than manual operations. In fact one could only use it in a very structured and therefore a less flexible way. In this way design choices become even more important as well as good ways to plan, schedule and control the use of the equipment. Much Operations Research was started on these aspects. Today, in 2001, another challenge is the continuous growth of container ships. Cullinane [10] states that much larger ships are to be expected and recently already 10,000 TEU ships were announced. This will put increasing pressure on terminals to speed up their handling, since the economies of scale of larger ships can only be realized if the handling speed at the harbors increases accordingly. So, more research is needed on this aspect as well (see e.g. Vickerman [61]).

2.2 Description of activities

In this section, we give a short overview of activities at a container terminal. In this we follow the sequence of events from the arrival of a ship until the departure of a container to an inland destination. We will briefly introduce the material handling equipment. A container terminal is based on a maritime interface. Hence it has quays with cranes to load and unload ships, a stack to store containers and an interface with inland transportation either by truck, rail or barge. The quay cranes are very large in order to handle the containers from sea-going vessels. The size of the latest generation of vessels is enormous; typically more than 300 m long, with a draft of 13 m, a beam of 42 m, implying 17 boxes across on deck (P&O Nedlloyd N series). Often one has smaller cranes to serve the feeder ships or the inland barges. Most quay cranes consist of an open structure with a beam extending over the ship. They have a trolley and a spreader to attach to the containers from the top, which are then moved by cables.

Once from the ship, the containers are put on a vehicle, e.g. a trailer or an automatic guided vehicle (AGV), which moves the container to the marine stack. This stack is the main decoupling point between the import and export flows, either from sea to sea or from sea to land and vice-versa. The stack may consist of containers on chassis (quite often in the USA), or, of containers stacked on top of each other in a certain pattern (more common in Europe and Asia, because of space restrictions). Normally only containers of the same type are put on each other. The stacking itself occurs by stacking cranes or straddle carriers. Stacking cranes can be rail-mounted (which is stable, fast, but unflexible), rubber-tired (more flexible) or be put on a concrete or steel structure (overhead bridge cranes). Apart from manually operated stacking cranes, there are also (semi-)automatic stacking cranes. An alternative system for the transport of containers to the stack is the use of straddle carriers. This equipment combines the functionalities of a stacking crane and a transport vehicle. A straddle carrier is able to drive over a container, lift it up (3 or 4 containers high) and move it around. Figure 1 shows several terminal equipment.

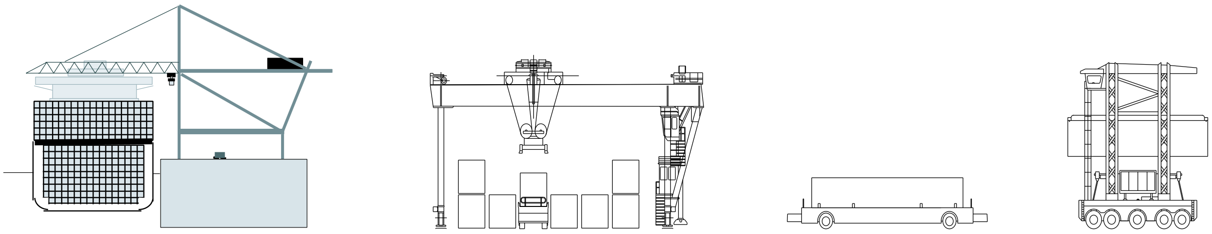

Figure 1: Terminal equipment: quay crane, stacking crane, AGV, straddle carrier

The stack on ground is usually organized into a block pattern which is served by one or more cranes. One main problem with stacking containers on top of each other is that when a bottom container is needed, the containers above it need to be reshuffled (put at another position in the stack). A random-access storage system, like an Automated Storage / Retrieval System in a distribution warehouse would circumvent these problems, yet to date none operates for maritime containers. Several (unpublished) studies have been done on these systems but the problem is that containers are much heavier (up to 30 metric tonnes) and larger compared to a pallet (one ton)), which makes the construction of such a storage system prohibitively expensive.

A container terminal can have several interfaces with inland transportation. First, there are transfer points for trucks, which are then loaded from the stack using straddle carriers, reach stackers or other cranes. Next, there can be a rail terminal or service center, where containers are loaded onto or from trains. Finally, there can be a barge service center where barges are loaded using specific equipment.

In Figure 2, a schematic view of a typical terminal is given, with all its main components like the quays, the stack and the landside interface.

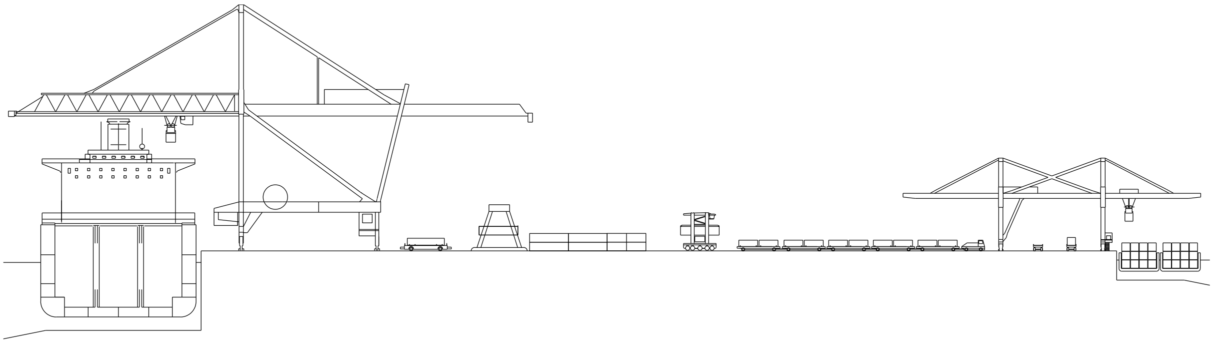

Figure 2: Schematic view of a container terminal

2.3 Classification of decisions

Decisions on container handling equipment and its scheduling can be categorized according to the time horizon involved. Usually, one distinguishes between strategic, tactical and operational decisions. Specific within the strategic level is the design of the terminal. There, one makes decisions on the choice of the handling equipment, on the way (or concept) in which operations are carried out as well as on the layout of the terminal. At the tactical level (months / weeks), one decides on capacity levels of equipment and manning, on layout structures and on timetables of ships and trains (in terms of frequency and day of week). Finally, on the operational level one decides on the allocation of capacity to the work to be done. One may even add a real-time level, where quite detailed control decisions have to be made regarding automated equipment, like which route to take for an AGV, which speed to use and when to make turns. But we will only sideways deal with these issues in this paper.

In the remainder of this paper, we will discuss a number of relevant decision problems that arise within container handling. For each problem, we will discuss at which level of decision making it appears.

2.4 Specific characteristics of container handling

One may wonder whether container terminals could not be treated as large, open-air variants of warehouses. Yet they differ from them in the following characteristics:

- Container terminals have more a flow through character than most warehouses. The average residence time varies from some few days to two weeks in container terminals, which is much less than warehouses.
- Containers are individual elements in a container terminal, while products are usually generic elements in a warehouse. This gives other problems in storing them (e.g. no A,B,C classification applies).
- Operations in a container terminal are usually somewhat more time-critical than in a warehouse. It is for instance not possible to postpone operations to a next day. Operations continue around the clock.
- The size of containers is much larger than of products in a warehouse. This implies that other handling equipment is necessary and that random access systems are not (yet) feasible. Although the size of containers does not directly effect planning problems, the specific characteristics of the handling equipment does.

3 Container stowage

Container ship stowage planning deals with the arrangement of containers within the ship. In general, a container ship calls at a number of ports on its route and in each port, containers are unloaded and loaded. The containers that are loaded are destined for a number of subsequent ports along the vessels route. The stowage problem considers the assignment of containers to positions in the ship such that the overall stability of the ship is maintained and the number of unnecessary movements is minimized. These unfavourable movements appear if at a certain port, containers have to be unloaded and reloaded again, since they are stored on top of containers destined for this port.

Containers differ in weight and size (20, 40 and 45 ft.). The placement of the containers in the ship should be such that the stability, torsion and strength of the vessel is maintained. Obviously, heavy containers are usually stored at the bottom of the vessel. The light containers are then stacked upon them. Moreover, containers of different size cannot be stacked on top of each other. Next to the weight and size considerations, a number of other restrictions has to be taken into account. For instance, reefer containers require electrical power, which is only available on specific positions in the ship. Certain containers carrying dangerous materials (with a certain IMO classification) have specific stowage requirements, which include separate stowage from other containers. Next to these technical restrictions, also the destination of containers has to be taken into account when the stowage plan is made. Obviously, if a vessels first calls port A and then port B, it is not desirable to stack containers destined for port B on top of containers for port A. This will lead to so called shifting moves.

Avriel et al. [3, 4] focus on the minimization of the number of shifting moves. The technical constraints on the stability of the vessel are left out in the model. In [4] they give a 0-1 programming formulation where the objective is to minimize the number of shifting moves. However, the problem is in NP (see also [3]) and solving the model to optimality cannot be done for real-life problems. As a result, a heuristic procedure is proposed. In a companion paper [3], Avriel et al. elaborate on the relation between stowage planning and the coloring of circle graphs.

Wilson et al. [66, 67] present a very realistic model, taking into account all technical restrictions in order to come to a commercial usable decision support system. Their approach is based on decomposing the planning process into two sub-processes. In the first process, called the strategic process, they create a rough stowage plan, based on grouping the containers with the same characteristics (size, port, etc.) and assigning them to blocks of storage space in the ship. These blocks represent a number of storage spaces below or above deck. The stability for this rough stowage plan can be calculated to an acceptable degree. In the second phase, called the tactical planning process, individual containers are then assigned to specific slots, resulting in a detailed stowage plan. In the strategic phase, Branch & Bound is used to assign the containers to the blocks in the ship. In the tactical planning process, packing heuristics together with Tabu Search are used to make the detailed assignment of containers to slots. This two level approach seems to be used in practice, where the carriers make the first rough plan and the terminals the more specific plan. Commercial packages exist for this problem, but according to Van der Ham [55] they seem to be based on greedy heuristics.

4 Berth and crane allocation

There are several categories of ships, with large ocean-going vessels as the most important ones and short-sea feeders and barges as the less important ones. A logical way of assigning arriving ships to the berths available seems to be in First Come First Served order within the respective category. However, this may not be a good strategy, especially when the handling time of a vessel depends on the berth it is assigned to. In container handling, this certainly is the case, since a common used stacking policy is to store the containers to be loaded on the same vessel in a more or less dedicated area of the stack. Hence, it is desirable that vessels berth relatively close to this area. In allocating a ship to a berth, one has to take the available berths into account as well as the available cranes to unload and load the ship. Scientific approaches to this problem can therefore be subdivided into pure berth allocation models and crane allocation models. Below we will discuss the contributions in more detail.

Imai et al. [21, 22, 43] consider the Berth Allocation Problem (BAP) in different versions. The BAP is the problem of assigning ships to berths, such that the sum of the waiting and handling times of the ships is minimized. Each berth can handle only one ship at a time and the handling time of a ship is berth dependent. The authors consider several versions of the BAP. In the static BAP, it is assumed that all ships have already arrived in the port at the beginning of the planning horizon. In this case, there is no idle time between the ships that are handled at a certain berth. The problem can then be formulated as a two dimensional assignment problem, which can be solved in polynomial time. In [21], the authors consider the static BAP under multiple objectives. Not only the sum of the waiting and handling times of the ships are minimized, but also the ship's dissatisfaction that arises from the berthing order. Although it is assumed that all ships are present at the beginning of the planning period, dissatisfaction may arise since the optimal berthing order with respect to the waiting and handling times, may not correspond with the order in which the ships arrived. The multiple objectives are handled by using the weighting method, which reduces the multiple objectives into a single one. By varying the weights, the set of noninferior solutions is identified.

In the dynamic BAP [22], the ships arrive during the planning period and as a result, there may be idle time between two consecutive ships serviced at a berth. As a result, the problem cannot be solved in polynomial time anymore. Based on a mixed integer programming formulation, Imai [22] develops a lagrangian relaxation, which is solved using the subgradient method. Another extension of the model is considered in [43]. In this paper, the authors consider the dynamic BAP in which it is allowed that more than one ship at a time is handled at a berth, as long as the total length of the ships is smaller than the length of the berth. Moreover, they include the additional constraint that a ship can only be served at a berth if its draft is less than the water depth of the berth. The problem is then formulated as a non-linear programming problem, which is solved using a genetic algorithm. Lim [38] also considers this problem and formulates the problem as a restricted version of a two-dimensional bin-packing problem. After proving NP-completeness he develops a heuristic using a graph theoretic model. Finally, Preston and Kozan [47] consider berth allocation such that the ships are close to the place where the containers to be loaded are stacked. They apply genetic algorithms to solve the berth allocation problem with the ships turn around time as objective.

Next to these analytical approaches there have been several simulation studies which employ decision rules for the dynamic allocation problem. We mention [20, 36, 37, 50, 70].

At a slightly more detailed level, the assignments of vessels to berths can be done by taking into account the assignment of the quay cranes to the vessels. Obviously, the number of quay cranes which are assigned to a vessel influences the handling time of the vessel. This results in the so called crane scheduling problem, which has been investigated by Daganzo [11] and Peterkofsky and Daganzo [46].

In the static crane scheduling problem [11], a number of quay cranes has to serve a number of ships such that the costs of delay of the ships is minimized. Both the berth and the ships are represented by slots. A slot corresponds to a hold of a ship. Each ship requires a certain number of adjoining slots at the berth and each hold can be handled by a limited number of quay cranes (usually 1). Moreover, it is assumed that at time zero, all ships to be handled have arrived at the berth. A mixed integer programming (MIP) formulation is given for this problem, which is only solved for small instances by enumeration. Furthermore, a heuristic procedure is designed which is based on some crane scheduling principles. In a companion paper by Peterkofsksy and Daganzo [46], an advanced Branch & Bound algorithm is presented in order to solve real-life instances.

The static crane scheduling problem can be generalized to allow for different arrival times of vessels and capacity restrictions on the berth (queuing of vessels). The proposed solution methods for the static case [11], can be modified to be used for the more general cases.

5 Container loading; quay transport

The loading of containers is done according to the stowage plan (see Section 3). That is, each container should be loaded at the position in the ship that was determined by the stowage planning. Moreover, from the quay crane scheduling (see Section 4) it follows which quay crane handles which holds of the vessel.

The loading process of a container ship consist of the retrieval of the containers from the stack, the transport to the quay and the loading of the containers by the quay cranes into the vessel. The unloading operation is the same but reversed. However, the unloading of a vessel is far less complex than the loading, since during the loading, the stowage plan has to be respected. Hence, the order in which the containers arrive for loading at the quay cranes is important. For containers that are unloaded, the order of unloading is not relevant.

Looking at container terminals worldwide, there are three commonly used handling systems for the quay transport. The first system uses stacking cranes for the retrieval of containers from the stack. These stacking cranes can either be rubber-tired or rail-mounted. In case of rubber-tired cranes, the cranes can usually switch from one stacking lane to another, depending on where the containers for a specific vessel are located. Although this implies more flexibility, changing from one stack lane to another is time consuming and is therefore not done so often in practice. After a stacking crane has retrieved the container from the stack, it loads the container onto a transport vehicle, usually a terminal truck or an automated guided vehicle. Usually such vehicle can carry one or two containers. However, some terminals use so called multi-trailer systems, capable of transporting 10 TEU. The terminal vehicle drives to the proper quay crane, which lifts the containers off the vehicle. At most terminals, the stacking cranes and terminal trucks are manually operated. Several terminals of ECT in Rotterdam however, have automated equipment. In theory, this does not make a lot of difference in the scheduling and control problems that arise, although the actions of drivers can never be completely coordinated. On the other hand, automated systems are much less flexible and lack driver's experience and insight. Therefore, detailed and efficient scheduling is much more crucial to achieve satisfactory performance at these automated terminals.

An alternative system for the quay transport of containers is the use of straddle carriers. Straddle carriers combine the properties of a crane and a vehicle. Hence, they are able to retrieve the containers from the stack and deliver them at the quay cranes. Note that since these vehicles can load and unload the containers themselves, they never have to wait for a crane (provided that there is a sufficient buffer capacity). Based on these arguments, the straddle carriers seems to be the ideal piece of terminal equipment. However, straddle carriers are very expensive and much more unreliable than a system of stacking cranes and terminal vehicles. Moreover, straddle carriers need more space in the stack to operate.

The third possible system is not used that many anymore; stacking all containers on chassis. Then only terminal trucks are needed to drive the trailers to the quay cranes where they are unloaded. Since each container is stored on a chassis, a lot of storage space is required. On the other hand, each container is directly accessible, which makes such a terminal easier to operate.

The choice which handling system to use for the quay transport of containers is typically a strategic issue. However, often the geographic location of a terminal determines which system will be used. For instance, due to extreme shortage of storage space, the Asian terminals like Hong-Kong and Singapore use a system of stacking cranes and terminal trucks, since stacking cranes allow for higher stacking, compared to a system of straddle carriers, which are limited to stack only 3 or 4 containers high. On the other hand, if storage space is widely available, for instance in the USA ports, a system using trailers will be preferred because of the relative ease to operate such a system. In Europe the situation is diverse. Although the stacking height is usually relatively low (2 to 4 containers high), both straddle carriers (Hamburg, Bremen, Rotterdam and Antwerp) and automated stacking cranes (ASC's) and AGV's (Rotterdam) are used. Within this context of deciding which handling system to use, we mention the work of Vis et al. [64] in which a simulation study is done comparing these two systems. They claim that on average, the number of straddle carriers required (for transport of containers only, not for stacking) is about 30 percent less than the number of AGV's required. This would favour the use of straddle carriers. However, when deciding on which system to use, also costs and reliability have to be taken into account, which usually do not favour straddle carriers.

In the next subsections, we will discuss various scheduling problems that arise at the quay transport. These problems all appear at the operational level. Obviously, the purpose is to use the available equipment in the most efficient way. However, the overall objective should be to minimize the in–port time of the vessels, in order to realize their economies of scale completely.

5.1 Scheduling of stacking cranes

Kim and Kim [30, 27] consider the optimization of the routing of a single stacking crane. Such a stacking crane operates on a stacking block, which is again divided into a number of bays. The stacking crane picks the containers from the stack and loads them onto yard trucks which transport the containers to the quay cranes. The containers to be retrieved by the stacking crane are divided into a number of categories. The categories are based on size, weight, destination port, etcetera. Each bay is assumed to be dedicated to a category, i.e., it only contains a certain number of containers of the same category. Several bays can contain containers of the same category. For the stacking crane, the work schedule is assumed to be given, that is, the sequence in which containers of a certain category have to be picked is given. The problem is then to determine the sequence in which the stacking crane visits the bays and the number of containers that is picked from a bay each time. Obviously, this has to be done in such way that the work schedule is satisfied. The problem is formulated as a mixed integer program on which an optimization algorithm using dynamic programming is based. In a related paper [28], a Beam Search algorithm is used to solve the model. The performance of the algorithm was tested using 360 sample problems. Moreover, for several smaller instances, the Beam Search solution is compared with the optimal solution. The authors report an average difference in performance of about 15 percent.

Murty et al. [42] consider the problem of deploying rubber-tired stacking cranes during several work shifts. They consider a terminal in which there are stacking blocks that have a certain workload in every shift. The stacking cranes are allowed to switch from one block to another. However, the number of switches is restricted to one per stacking crane, since the movement of such a crane from one block to another is time consuming and moreover, the roads between the blocks are obstructed for the terminal trucks. The objective is to assign the stacking cranes such that the amount of workload that cannot be finished within a shift is minimized. Next to a mixed integer programming formulation, also an approach based on Lagrangian relaxation has been developed. However, one of the shortcomings of these models is that they assume that all work is available at the beginning of each period, where in practice, the work "arrives" during the period. Moreover, terminal operators considered the approaches to complicated for practical implementation. Therefore, an alternative heuristic approach was developed, based on expert judgment of crane supervisors.

5.2 Scheduling of AGV's

Although AGV systems also appear in flexible manufacturing systems [18] and warehouses [56], the scheduling and control problems that appear at automated container terminals are much more complicated. For instance, deadlocks and congestion are major problems. This is mainly due to the large number of vehicles that is deployed and the large size of the vehicles themselves. For instance, the number of AGV's working at the loading operation of a single vessel is about 30, while their length is some 17 meters and width 2.5 meters. Moreover, the scheduling of the AGV's also interferes with the schedules of the quay cranes and the stacking cranes, which is a complicating factor (see also Subsection 5.4).

The scheduling of AGV's is considered in [9, 25]. Chen et al. [9] consider the dispatching problem of AGV's in an automated container terminal. To simplify the analysis, they assume that stacking cranes are always available to load or unload the AGV's. For the case of a single quay crane, which is either loading or unloading, they derive a greedy algorithm for assigning the jobs to the AGV's, which is shown to be optimal. For the case of multiple quay cranes, the greedy algorithm does not necessarily give the optimal solution and is therefore used as a heuristic. The algorithm was tested within a simulation model in order to investigate its effectiveness and robustness. Moreover, a queueing model was developed. Given the use of the greedy dispatching policy, this model gives insight into the effects on the performance of using more AGV's, more cranes, etcetera.

Another approach to the scheduling of AGV's is given by Kim and Bae [25]. For each container to be transported, they introduce event times which have to be met. These event times define the exact pickup and delivery times of each container. For the case of a single quay crane and the given event times, they reduce the dispatching problem of AGV's to an assignment problem. Next, for the case in which the event times cannot be met, a heuristic is developed.

Work on dispatching rules for AGV's in a more general context was done by Egbelu and Tanchoco [18] and Van der Meer [56]. Although dispatching rules seem to be generally applicable, the specific context of an automated container terminal does not allow for a straightforward implementation, as was shown in Meersmans and Wagelmans [40]. Hence, to apply these dispatching rules at an automated container terminal, like the ECT terminal in Rotterdam, they need to be adjusted (see Meersmans and Wagelmans [40]).

Vis et al. [63] consider the problem of determining the number of AGV's required at a semi-automated container terminal. They describe a model and give a minimum flow algorithm to solve the case in which containers are available for transport at given time instants. Unfortunately, such information is in reality only available on short time-instances and changes constantly over time.

5.3 Traffic control of AGV's

Next to the scheduling of AGV's, another main issue is the control of them. Although AGV's at container terminals are free ranging, they do follow fixed paths for their routes. Moreover, since the orientation of containers (the direction of the doors) is prescribed both at the ship as in the stack, the AGV's have to make complex turns, which require lots of space. The traffic control mechanism should guarantee that the AGV's do not collide. For instance, if the paths of two AGV's cross, the control mechanism should determine which AGV goes first and which AGV has to wait. Or whenever there are two parallel curves, only one of them can be used by an AGV at a time, since the other is then blocked.

The control system can either be central, so the control is done by a central system, or distributed, which implies that the AGV's and certain areas possess a form of intelligence. The current generation of automated container terminals in Rotterdam uses a central control system. However, Evers and Koppers [19] propose a distributed control system using a hierarchical system of semaphores. Roughly speaking, the semaphores act as a kind of traffic lights that control the number of AGV's that enter a zone. The advantages of the approach are the flexibility in modeling a transportation system and the less amount of communication that is needed to control the AGV's (the AGV's communicate only with local areas). Although one of the purposes of the traffic control system should be to make the AGV travel times more predictable, they are still stochastic, making the the dispatch a difficult scheduling problem, since sending the AGV's earlier on their way causes even more traffic and sending them late may cause them to arrive too late. Finally, the strict loading order at the QC's also causes problems. Since the AGV's should arrive in a certain order at the QC's and overtaking in the queue (AGV track) in front of the QC is not possible, the traffic control system should guarantee that the AGV's enter the queue in the right order. Taking into account the specific difficulties of the AGV system at a container terminal, Duinkerken and Ottjes [17] have performed extensive simulation studies in order to investigate the performance of such a system under intelligent traffic control.

5.4 Integrated scheduling of stacking cranes and AGV's

The main loss of performance at a container terminal that uses stacking cranes for the retrieval of containers and AGV's (or terminal trucks) for the quay transport, is the fact that the schedules of the various equipment are uncoordinated. Hence, empty AGV's are waiting for stacking cranes to load the next container and vice versa. In the worst case, even deadlock situations may appear. Therefore, Meersmans et al. [39, 41, 40] propose to schedule quay cranes, stacking cranes and AGV's in an integrated way. Their models explicitly take into account the topology of the terminal. For the case in which all AGV's pass a common point after unloading at the QC's (the current situation at ECT's Delta terminals), it can be shown that the order in which the AGV's start at the common point to pick up their next container, completely determines the remaining part of the schedule, also for the stacking cranes! Using this result, Meersmans and Wagelmans [41] present a Branch & Bound algorithm that uses several combinatorial lower bounds to cut off unpromising parts of the search tree. These lower bounds turn out to be very effective, since the algorithm performs well not only on small instances, but also on large real-life problems. Moreover, based on this Branch & Bound algorithm, a heuristic Beam Search algorithm is developed. In most cases, this Beam Search heuristic gives a solution that is within 5 percent of the optimum, requiring far less time than the Branch & Bound algorithm. A dynamic version of the Beam Search algorithm is discussed in [40]. In this paper, the authors also propose a number of dispatching rules, whose performance is compared with the Beam Search algorithm in an extensive computational study.

For the case in which the AGV's do not pass a common point after unloading, for instance, if the AGV's are allowed to take shortcuts directly after unloading at the quay crane, Meersmans et al. [39] present a mixed integer programming formulation for which several classes of valid inequalities are derived.

5.5 Scheduling of straddle carriers

An alternative handling system for the quay transport of containers by stacking cranes and AGV's (terminal trucks), are straddle carriers. Unlike AGV's, straddle carriers are able to pick up and drop off containers themselves. As a result, straddle carriers can be used for both the retrieval of containers from the stack and the transport to the quay cranes. However, in order to overcome the dependency of the AGV's on the stacking cranes, straddle carriers are also often used for transport purposes only.

Böse et al. [6] consider the dispatching of straddle carriers for several loading and unloading operations (vessels) at the same time. They use a genetic algorithm to minimize the delays of container transfers to the quay cranes. Next to a situation in which there is a static assignment of straddle carriers to quay cranes, they also investigate the effects of a dynamic assignment, i.e., the pooling of the straddle carriers. Computational test are done for multiple loading and unloading operations and for different layouts of the terminal. The results show that a dynamic assignment can lead to significant productivity improvements.

Work done by Winter [68] concentrates on combining the stowage planning of the vessel with the scheduling of the straddle carriers. This is done as follows. The containers that are to be loaded are divided into a number of categories, based on size, weight, destination port, etcetera. For each quay crane, a sequence of categories to be loaded is then given. Hence, during the loading of the vessel, there is still freedom with respect to the choice of the specific container that is delivered, provided that the container is of the proper category. This additional freedom allows for the optimization of the movements of the straddle carriers. For the case of a single quay crane, a mixed integer programming model is given, which provides optimal or near optimal solutions in short time. For multiple quay cranes a best-fit heuristic is proposed.

Kozan and Preston [34] consider the optimization of container transfers by straddle carriers (called yard machines). The objective is to minimize the time the vessels stay in the port. Their model explicitly deals with the reshuffling of containers, by introducing setup times. These setup times depend on the order in which all containers on top of a specific container are handled. The model presented is solved by using genetic algorithm techniques. In a companion paper, Preston and Kozan [48] solve the model using a tabu search heuristic. Computational results show that in most cases, the tabu search gives better solutions than the genetic algorithm, in far less time.

The tabu search heuristic is also used investigate the effects of different stack configurations on the time needed to transfer all containers to the quay.

6 Stacking

The stack allows the various transport activities to occur independently of each other. Would there be no stack then every container ship arrival would have to be followed by direct unloading to inland barges or to trucks, which is a too complex logistical operation because all arrivals would have to be coordinated, which would both cause much congestion and be susceptible to inevitable delays. As discussed in Section 2, different stacking systems exists. In this section we will only consider stacking in piles on the ground, which is done at most terminals.

Some containers (e.g. reefers) require special locations, because they need to be supplied with electricity. The determination of the stack capacity is a major design problem of a terminal, as the stack occupies much costly land. Stacking high may be advocated, but the expected number of reshuffles increases sharply with the stacking height. A reshuffle is an unproductive move of a container which is required to access another container that is stored beneath it. This is illustrated in Figure 3, container 1 is directly accessible, container 2 demands one reshuffle.

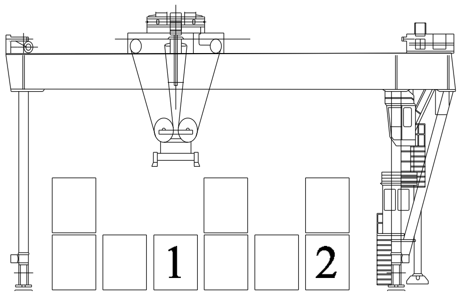

Figure 3: Reshuffles

Related to the stack capacity is its layout: how long and wide will it be and how many blocks or lanes will be used. Next one has to decide in the design what type of equipment will be used for stacking. The two most common types are straddle carriers and stacking cranes. Next to these two, some terminals operate with a stack on wheels, in which all containers are put chassis. Obviously, this requires a large storage area and high investment costs in chassis.

Quite often stacks are separated into import and export parts. Import containers usually arrive in large container ships and hence, in a somewhat predicted way. Yet they are likely to depart in an unpredictable order, so, they cannot be stacked that high. Export containers may arrive somewhat randomly, but their departure is usually connected to a ship and hence, they can be stacked in a much better way.

At the tactical level, one has to decide on allocation of parts of the stack to certain activities (e.g. ships). At an operational level, one has to decide on which container to stack where in order to avoid reshuffles as much as possible. Note the close relation to the stowage planning as discussed in Section 3. Also in the stowage planning, containers are stored on top of each other, such as to minimize the number of reshuffles. However, the stacking problem can be considered more difficult since there can be uncertainty about which container will be needed before another. For import containers, this uncertainty exists because trucks arrive more or less randomly to pick up a specific container. For export containers, it is usually known with which ship they depart. However, the stowage plan is usually available only shortly before the loading starts and thus, most containers are already stored in the stack. This leads to reshuffles which result in a slowdown of the loading operation. In case the stowage plan is available earlier, the containers in the export stack may be re-marshalled. This results in "ideal" stack and thus, less handling work during the loading operation of the vessel. Kim and Bae [24] describe a two stage approach in order to minimize the number of containers to be moved and to do so in the shortest possible travelling distance. Although such a re-marshalling approach seems very attractive, it is not often possible to do so. As already mentioned, the stowage plan is only known shortly before the loading operation. Moreover, building up this "ideal" stack also requires additional storage space which may not be available.

Stacking problems can be dealt with in two ways: simplified analytical calculations or detailed simulation studies. The first gives insight into the relationships between the various parameters on a more abstract level. The second can go in much more detail, with the negative by-effect that it is time consuming and only few people really understand its ins and outs. No comprehensive stacking theory exist today, and a good stack design not only depends on local space conditions but also on the information characteristics of the ingoing an outgoing flow of containers which may vary from port to port. Examples of both approaches are given below.

Sculli and Hui [49] were among the first to develop yardsticks for the relation between stacking height, utilization (or storage space needed) and reshuffles by applying a comprehensive simulation study. Taleb-Ibrahimi et al. [54] discuss this relation for export containers both at a long-term scale as well as operationally. They discuss dynamic strategies which store early arriving containers in a rough pile, until a certain date, after which all containers for a ship are put in a dedicated storage area (usually close to the berthing place of the ship). The procedures developed calculate the storage space needed as function of the stacking height. De Castilho and Daganzo [13] continue these studies with the stacking of import containers. They consider two strategies, one which keeps stacks of the same size versus one which segregates the containers on arrival time. A slightly more detailed discussion resulting in tables and yardsticks (looking at stacking blocks with bays of similar sized containers), both analytically and by simulation, was given by Kim [23]. Kim and Kim [31] extended these studies by also taking the number of stacking cranes into account. They developed a simple cost model for optimizing this number using analytical approximations for the various performance measures.

Segregating space allocation strategies of import containers were studied by Kim and Kim [26]. In segregation strategies, stacking newly arrived containers on top of earlier arrived containers is not allowed. Spaces are thus allocated for each arriving vessel. They study cases with constant, cyclic and varying arrivals of vessels.

An empirical statistical analysis of the actual performance at a Taiwanese container terminal was provided by Chen et al. [8]. The number of shift moves was related to the storage density, the volume of containers loaded and the volume of containers discharged both for stacking crane blocks and straddle carrier blocks.

More popular discussions of the effect of different stacking heights appeared in the professional journal Cargo Systems, cf. [2, 12, 65].

The relation between space allocation and the transport of the containers using vehicles to it, is studied using combinatorial optimization by Demir et al. [15]. They look for strategies for dispatching the vehicles to minimize the total time to download all the containers from the ship. They prove both NP-hardness of the problem and derive absolute and asymptotic worst-case performance ratios of the heuristics. Murty et al. [42], consider storage space assignment, taking into account congestion that may appear if too many terminal trucks have to deliver (pick up) containers in the same area of the stack. A two stage method is proposed. First, the arriving containers are assigned to blocks in the stack. Next, each container is put in the best position in its block, taking into account possible reshuffles. Stacking policies are investigated by Duinkerken et al. [16], who use a detailed simulation model that not only models the stack, but also the quay transport in an automated container terminal.

Decision rules using weight groups for locating export containers were derived and validated through dynamic programming by Kim et al. [29]. Weight is a useful criterion since heavy containers are usually stored deep in a ship (see also Section 3).

In a recent study, Dekker et al. [14] consider the effect of creating groups of exchangeable containers in the stacking. They show that having such groups not only lowers the number of reshuffles considerably, but that also the workload during the loading of the vessel can be much more evenly distributed in automated systems. Unfortunately, such exchangeable groups are only likely to be created for export containers, not yet for import containers. Hence, for the latter, stacking remains a severe problem.

7 Overall terminal studies

Container terminals can grow out into large complexes with several marine terminals, empty depots, container repair centers, rail terminals, barge service centers, etcetera. Studying a whole container complex and the relation between all the components is therefore the last aspect of container terminals we like to discuss. The literature on this aspect is somewhat scattered and we like to distinguish the following groups. First of all, there is the design of an overall terminal complex. Next, there is the study of the various other interfaces of a terminal with other modalities, like a rail terminal, and finally, there is the study of all the transport streams in and between the various complexes.

7.1 Overall container terminal design

Consultants often apply spreadsheet methods to this as little detailed information is known and quick answers have to be provided using yardsticks and experience. Little of these approaches have been published. A more detailed model is described in Van Hee et al. [57, 58], which describes a decision support system (DSS) for capacity planning at container terminals. The model uses several analytical models that are integrated within a single DSS. The DSS contains models for computing service times of stacking cranes, throughputs of quay cranes and the behaviour of the whole terminal. Another contribution on tactical level (months) capacity planning is Zaffalon et al. [71], which give a network model for resource allocation of terminal equipment over a number of shifts. A detailed simulation model is presented that is used to validate the resource allocation.

7.2 Rail terminals

Productivity at rail terminals is studied by Kozan [32] and Van Zijderveld [59]. Using probabilistic calculations, Kozan [32] determines the performance of various handling activities at a rail terminal. A much more complex study on a rail terminal, using simulation, was carried out by Van Zijderveld. He considered loading and unloading of trains at a rail terminal with two concepts: one in which trains stayed shortly at a terminal and were shunted to a shunting yard quickly thereafter, and a rail service center where trains stay relatively longer, but without a shunting yard. The point is that when multiple trains are handled at the same time, productivity can be improved.

7.3 Terminal layout and transportation

Transport in and between several terminals can be time critical, as incoming sea containers may have to be loaded on a train during the time window the train is on the terminal. Hence a good layout is essential for efficient operations. The transport may be done with single trailers, multi-trailer systems or straddle carriers.

Few papers have addressed these issues in a comprehensive way and in fact only scattered results are available so far. Therefore, we just mention all individual papers.

Kozan [34, 33] considers container transfers at a (multimodal) terminal complex. He models the problem as a large network with a mathematical programming formulation which he then solves with genetic algorithms. Some of the elements within this formulation are expected throughput times based on probalistic calculations. He applies the technique to the Brisbane Multimodal Terminal and identifies and solves bottlenecks using sensitivity analysis.

In Kurstjens et al. [35] and Ottjes et al. [44], a study is described on the best transportation system for inter terminal transport at the Rotterdam Maasvlakte (where ECT resides). Three transportation systems were compared, viz. a multi-trailer system capable of transporting 10 TEU, an AGV system using existing AGV's and a new system using a so-called automatic lift vehicle (ALV), comparable to an automated straddle carrier. From the study it appeared that all systems have different characteristics and that there was quite some diversity in their logisitic performances. The first two systems needed cranes to put their load on them, which caused for quite a bottleneck in the handling, while the ALV could put its container at its destination on the ground and continue with another job. Accordingly, in the scenario studied, about 65 ALV's had the same logistical performance (the same number of containers transported within prescribed time windows with about the same number (1%) too late) as 130 AGV's. As the multi-trailer systems had decoupleable (manned) trucks from their trailers, some 22 trucks were needed with some 130 trailers (each capable of carrying 10 TEU) to achieve the same performance. As the outcomes depended strongly on the way the transports were planned and controlled, quite a large part of the study concentrated on these aspects. These problems turned out to be much more difficult than ordinary vehicle scheduling problems, because of the interfacing with cranes to finish jobs and the many stochastic elements.

Steenken et al. [52, 53] consider the routing of straddle carriers that have to perform internal and landside moves. Each move has to be carried out before a certain due date. The problem is modeled as a Multiple Rural Postman Problem and two kind of heuristics are used for solving it. The first heuristic comes from the field of printed circuit board assemblies. The second class of heuristics are dispatching rules like the Earliest Due Date (EDD) and Shortest Processing Time (SPT) rule. A detailed simulation model for straddle carriers that have to perform landside tasks is described in Behera et al. [5]. The authors model the route network of the terminal and take into account the delays that may appear if too many straddle carriers operate in the same area.

Wong et al. [69] present a generic simulation model for terminal layout and the determination of the type and number of handling equipment. They apply it to an hypothetical terminal. Generic yardsticks for handling productivity at a container terminal are given by Al-Kazily [1].

A new terminal concept for short sea shipping is described by Ottjes and Veeke [45, 60]. In this concept, containers are stored on frames, which are picked up by AGV's who drive into the vessel. This concept can be compared with the traditional "roll on roll off" systems that exist nowadays. Simulation was used both for proving the feasibility of the concept and for getting insight into the dimensioning of such a terminal.

Sinclair and Van Dyk [51] consider the problem of pick up and delivery of containers by road transport from a container depot. The problem differs from the well known pickup and delivery problem in the sense that trailers are used for the transport of containers. Whenever a truck arrives at a client or the depot, it can either leave only the container, or both the container and the trailer. The problem is solved using a two stage heuristic procedure.

8 Conclusions

Container terminals are very specific from a material handling point of view, because of the specific characteristics of containers. Terminals have become increasingly important and more and more scientific literature is devoted to them. This is even more true for the few semi-automated terminals which are being erected to cope with the increase in labor costs. The further increase in ship sizes makes a productivity improvement in container handling more important and therefore more specific research is to be expected. This overview has tried to classify existing scientific approaches and makes an attempt to confront scientific theory with the actual problems at container terminals.

Scientific theory on container terminals consists of general descriptions, yardsticks, simulation and analytical models. Each has its pros and cons. Our experience with ECT's automated terminals shows that the real problems are extremely complex and that existing approaches need much more development to help in taking the very costly decisions.

Operations Research has made valuable contributions for container terminals. The techniques employed vary from integer programming formulations, queueing models and simulation approaches. The first are used for planning under several constraints. The second are used to model and understand some of the queueing phenomena at terminals. The latter are used to gain more specific insight in case many operational aspects are included. Yet they provide less generic insights and the many details included make it difficult to claim generality of the results.

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