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Invited Review

Transshipment of containers at a container terminal: An overview

Iris F.A. Vis *, René de Koster

Rotterdam School of Management, Faculteit Bedrijfskunde, Erasmus University Rotterdam, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands

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Abstract

At container terminals, containers are transshipped from one mode of transportation to another. Within a terminal different types of material handling equipment are used to transship containers from ships to barges, trucks and trains and vice versa. Over the past decades, ships have strongly increased in size, up to 8000 TEU (Twenty feet equivalent unit container). In order to use these big ships efficiently, the docking time at the port must be as small as possible. This means that large amounts of containers have to be loaded, unloaded and transshipped in a short time span, with a minimum use of expensive equipment. This paper gives a classification of the decision problems that arise at container terminals. For various decision problems, an overview of relevant literature is presented. Quantitative models from this literature, which try to solve the problems are discussed. Finally, some general conclusions and subjects for further research are given.

Keywords: Logistics; Container terminal; Literature overview; Material handling equipment

1. Introduction

Containers are large boxes, that are used to transport goods from one destination to another. Compared to conventional bulk, the use of containers has several advantages, namely less product packaging, less damaging and higher productivity (Agerschou et al., 1983). The dimensions of containers have been standardised. The term twenty-feet-equivalent-unit (TEU) is used to refer to one container with a length of twenty feet. A container of 40 feet is expressed by 2 TEU.

Several transportation systems can be used to transport containers from one destination to another. Transport over sea is carried out by ships. On the other hand, trucks or trains can be used to transport containers over land. To transship containers from one mode of transportation to another, ports and terminals can be used. For example, at a container terminal, a container can be taken off a train and placed on a ship.

Containers were used for the first time in the mid-fifties. Through the years, the proportion of

* Corresponding author. Tel.: +31-10-4081719; fax: +31-10-4089014.

E-mail addresses: ivis@feweb.vu.nl, i.vis@fbk.eur.nl (I.F.A. Vis).

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cargo handled with containers has steadily increased. As a result of the enormous growth, the capacity of ships has been extended from 400 to 4000 TEU and more. Furthermore, the importance of ports and terminals has grown. With the introduction of larger ships, small terminals have changed into large terminals. To ensure a fast transshipment process, at large terminals, control for efficiency and a high degree of coordination is necessary. These terminals can be obtained by using, among other things, information technology and automated control technology. For example, in Wan et al. (1992), it is shown that the application of information technology in the port of Singapore results in more efficiency and a higher performance. In Leeper (1988) it is concluded that, in order to achieve an improvement of productivity and reduction in investment costs, an advanced automated control technology is a necessary condition.

Within a terminal different types of material handling equipment are used to transship containers from ships to barges, trucks and trains and vice versa. The containers can be transshipped directly from one mode of transportation to another. On the other hand, containers can also be stored in a storage area for a certain period, before they are transferred to another mode. First of all, the layout and the choice of equipment has to be determined. This is a necessary condition to obtain an efficient terminal. Furthermore, planning and control concepts for the different types of material handling equipment have to be developed. These concepts should result in a sufficient performance. In practice, most concepts are developed with the use of simulation or based on practical experience of decision makers. Furthermore, much research is done in this area, results of which could be incorporated in real terminals.

We can distinguish between three planning and control levels in making decisions to obtain an efficient terminal, namely the strategic level, the tactical level and the operational level. At the strategic level it is, for example, decided which layout, material handling equipment and ways of operation are used. The time horizon of decisions at this level covers one to several years. These decisions lead to the definition of a set of constraints under which the decisions at the tactical and operational level have to be made.

At the tactical level, it is decided which type of information is used and which broad choices have to be made. An example of a decision, that has to be made is: which ways of storing containers should be used? The time horizon of these decisions covers a day to months. Finally, at the operational level all detailed daily problems are solved, like where a certain container should be stored.

In this paper, the most common used types of material handling equipment at container terminals are discussed. For every system, various decision problems and solution approaches are treated. For each of the decision problems an overview of relevant literature is given.

The organisation of the paper is as follows: Section 2 describes the processes at container terminals. The planning of a complete terminal is examined in Section 3. Finally, some general conclusions and subjects for further research are given.

2. Processes at container terminals

Ships are nowadays unloaded and loaded at large terminals. The unloading and loading process at a typical modern container terminal is illustrated in Fig. 1. This loading and unloading process can be divided into different subprocesses, described below. When a ship arrives at the port, the import containers have to be taken off the ship. This is done by Quay Cranes (QCs), which take the containers off the ship's hold or off the deck. Next, the containers are transferred from the QCs to vehicles that travel between the ship and the stack. This stack consists of a number of lanes, where containers can be stored for a certain period. The lanes are served by systems like cranes or straddle carriers (SCs). A straddle carrier can both transport containers and store them in the stack. It is also possible to use dedicated vehicles to transport containers. If a vehicle arrives at the stack, it puts the load down or the stack crane takes the container off the vehicle and stores it in the stack. After a certain period the containers are retrieved

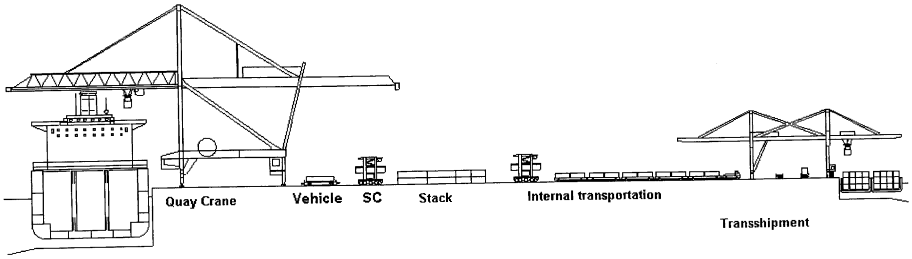

Fig. 1. Process of unloading and loading a ship.

from the stack by cranes and transported by vehicles to transportation modes like barges, deep sea ships, trucks or trains. This process can also be executed in reverse order, to load export containers onto a ship.

Most of the terminals make use of manned equipment, like straddle carriers, cranes and multi-trailer-systems. However, a few terminals, like some terminals in Rotterdam, are automated. At such terminals automated guided vehicles (AGVs) may be used for the transport of containers. Furthermore, the stacking process can also be done automatically by automated stacking cranes (ASCs).

In this section different subprocesses and their corresponding types of material handling equipment are described in more detail. In Fig. 2 all subprocesses are illustrated. The processes of Fig. 2 correspond to the systems of Fig. 1. Furthermore, different decision problems of the various types of material handling equipment are presented. Ways of solving these problems are also discussed.

2.1. Arrival of the ship

When a ship arrives at the port, it has to moor at the quay. For this purpose, a number of berths (i.e. place to moor) are available. The number of berths that should be available at the quay is one of the decisions that has to be made at the strategic level. In Edmond and Maggs (1978) queueing models are evaluated, which can be used in making this decision. They conclude that some of these queueing models can be used when the model and parameters are chosen carefully and the results are evaluated precisely.

One of the decisions at the operational level is the allocation of a berth to the ship. In Imai et al. (1997) it is studied how to allocate berths to ships while optimising the berth utilisation. On one hand optimal berth allocation can be obtained by minimising the sum of port staying times. As a result, ships moor at the quay according to the first come first served principle. On the other hand berths can be allocated, without consideration of ship's arrival order, by allocating ships at a berth

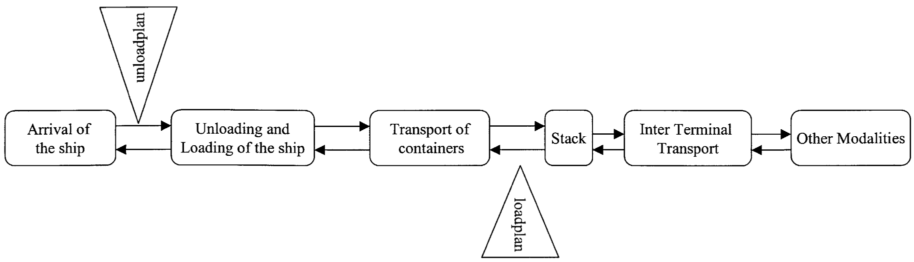

Fig. 2. Processes at a container terminal.

closest by the area in the stack in which most containers for this specific ship are located. As a result, the resulting terminal utilisation will be maximal, but ship owners will be dissatisfied by the long waiting times of the ships. Consequently, a trade-off exists between the total staying time in the port and the dissatisfaction of ship owners caused by the order in which ships are berthed. The berth allocation problem could be considered as a machine scheduling problem. However, the introduction of a multi-objective approach is according to Imai et al. (1997) really new in machine scheduling problems. A two objective non-linear integer program is formulated to identify the set of non-inferior berth allocations which minimises the dual objectives of overall staying time and dissatisfaction on order of berthing. Overall staying time equals the sum of the staying time of each ship, which exists of the waiting time until the berth is available and the berthing time itself. Dissatisfaction equals the sum of the number of cases in which a ship arrives later and is mooring earlier than a particular ship.

After defining the two objective non-linear integer program, the problem has to be reduced to a single objective problem. The resulting single objective problem is similar to the classical assignment problem. The objective consists of two parts, namely the sum of the waiting times plus the sum of dissatisfaction. To identify the set of solutions, generating techniques can be used which do not require prior statements about value judgments, like preferences and priorities, of the objectives. The generation method used in this paper is the waiting method. The set of non-inferior trade-offs between the first and the second term of the objective is identified by varying the value of weights. From numerical experiments, it can be concluded that the trade-off increases if the size of the port increases.

2.2. Unloading and loading of the ship

The number of import containers that has to be unloaded at the terminal is in practice usually only known shortly before the arrival of the ship. The unloading plan indicates which containers should be unloaded and in which hold they are situated in the ship. Successively, these containers are unloaded. Within a hold the crane driver is almost free to determine the order in which the containers are unloaded. The unloading time of a container depends on its place in the ship. Consequently, a large variance occurs in the container unloading times.

In contrast with the unloading process, there is hardly flexibility in the loading process. To ensure fast and efficient transshipment of containers, a good distribution of containers over the ship is necessary. Therefore, at the operational level a stowage planning is made. According to Shields (1984), the containers, that will be stowed, have to satisfy a variety of constraints, which arise as a result of physical limitations of the ship and containers and the sequence in which ports are visited by the ship. In Shields (1984) a system is presented which can assist in this planning process. The stowage problem is solved with the Monte Carlo method. Many different possible ship loadings are generated and the most efficient one is given. This system has been used worldwide since 1981. The most efficient plan is displayed with the precise loading order of export containers. For every container the exact place in the ship is indicated.

According to Wilson and Roach (2000), the container stowage problem is a problem, the size of which depends upon the capacity of the ship and the supply and demand of containers at each port. Finding an optimal solution is not realistic within reasonable times, because of the fact that the stowage plan has to be made across a number of ports. Therefore, the authors propose to decouple the process into two subprocesses, namely a strategic and a tactical planning process. In the first process, generalised containers are assigned to a block in the ship. Secondly, specific containers are assigned to specific locations within the blocks determined in the first phase. The block stowage problem can be solved by applying a branch and bound algorithm. The problem in the tactical phase can be solved by applying tabu search. In this way, good but not always optimal solutions will be found within reasonable computation times.

As described, decisions have to be made for questions that arise at three different levels. One of the decisions that has to be made at the strategic level is, which type of material handling equipment will be used for the unloading and the loading of containers from the ship. QCs are used both at an automated and a manned terminal. QCs are manned because automation of this process encounters practical problems, like exact positioning of containers. An illustration of a QC is given in Fig. 3. The QCs are equipped with trolleys that can move along the crane arm to transport the container from the ship to the transport vehicle and vice versa. The containers are picked with a spreader, a pick up device attached to the trolley. The QCs move on rails to the different holds to take/put containers off/on the deck and holds. It can occur that at the same moment one QC is unloading a container and another QC is loading one.

At the tactical level, one of the decisions that has to be made, is the exact number of QCs that work simultaneously on one ship. Nowadays, it is necessary to carry out the process of unloading and loading very fast to satisfy customers demand. Therefore, it is necessary to minimise the delay of ships.

The most general case of the crane scheduling problem, is the case in which ships arrive at different times in the port and queue for berthing space if the berths are full. The objective in this case is to serve all the ships while minimising the total delay of the ships. In Daganzo (1989) ships are described by the number of holds they have. Only one crane can work on a hold at a time. Daganzo (1989) discusses the static crane allocation problem in which a collection of ships is available at a berth to be handled at the start of the planning horizon and no other ships will arrive during this planning horizon. A number of identical QCs have to be allocated to the holds to minimise the total delay (i.e. costs) of the ship. The problem can be formulated as a mixed integer program. The solution indicates the average number of cranes used on each hold at every instance. As a result, an implementable crane allocation scheme has been found. Due to computational reasons, this exact solution method is only usable for a small number of ships. When a mathematical programming solution is not effective a heuristic procedure based on some scheduling principles, derived from optimal solutions, can be applied to solve the studied problem.

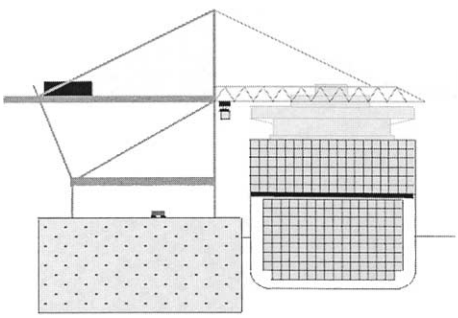

Fig. 3. Quay crane.

The dynamic case of the crane allocation problem is also studied. Within a finite horizon, ships arrive at instants within the horizon and cannot be handled before those instants instead of having ships ready at the start of the horizon. It is required to repeat the static allocation procedure for ships at the berth after each ship's arrival. Only loads remaining in the ships have to be considered. As a result, an arriving ship can get pre-emptive priority over a ship that is already being served.

For all described methods, it is assumed that cranes can operate on all ships present at the port. A formulation and solution method for the general case in which berth length is limited, is not provided in this paper. However, the results in the paper may lead to analytical expressions to predict crane productivity and ship delay, which is useful for the design of the terminal.

The minimisation of the total delay of ships is also studied by Peterkofsky and Daganzo (1990). The goal of this paper is to give an exact solution method for a class of problems considered in the paper of Daganzo (1989). This is interesting for practical use and theoretical use to test the performance of the heuristic methods. The problem is decomposed into two stages, namely finding the best departure schedule for the ships and finding a crane allocation scheme. A branch and bound method is given to solve the static case of the crane scheduling problem. This method is based on the property that the optimum is restricted to only certain kinds of departure schedules. It is proved that the search for the optimum can be restricted to boundary points. Boundary points are feasible schedules that lie on the boundary between the solution space's infeasible and feasible regions. Ten problems, based on real world problems are generated to test the method. The performance declines quickly when the problem size grows. According to the authors the described model can be extended to take into account ships with different known arrival times. Furthermore, the model can be applied in other situations, like machine scheduling problems.

The results for the static case from the heuristic method based on principles in Daganzo (1989) and from the branch and bound approach in Peterkofsky and Daganzo (1990) are compared in the paper of Daganzo (1989). For small problems with four ships, it can be concluded that the principal based approach is comparable to a formal optimisation procedure, like a branch and bound method. In larger cases, the use of the principal based approach is preferred over the branch and bound approach due to rapidly increasing computation times. However, the performance of the principal based approach is not tested for large problems.

Decisions at the operational level, such as which crane places which container in the ship and which container should be taken out of the hold first, are in practice made by the crane driver or determined by the loading and unloading plan. No literature has been found, studying this kind of problems.

2.3. Transport of containers from ship to stack and vice versa

As described containers have to be transported from the ship to the stack and vice versa. When the terminal is designed, one of the decisions at the strategic level concerns the type of material handling equipment, that takes care of the transport of containers. For the transport of a single container at a manned terminal, vehicles like forklift trucks, yard trucks or straddle carriers can be used. Straddle carriers, see Fig. 4, and forklift trucks can pick up containers from the ground.

A crane is needed to put the container on the yard truck. According to Baker (1998) the use of straddle carriers instead of non-lifting trucks can mean improved QC productivity. For the transport of multiple containers, multi-trailer systems can be used, see Fig. 5. This system, in this figure, uses a truck that pulls five trailers, each capable of carrying 2 TEU.

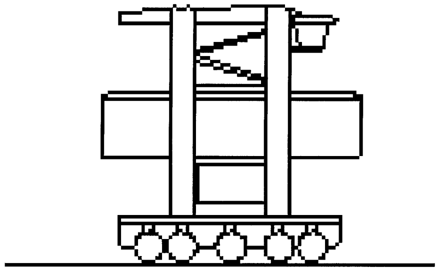

Fig. 4. Straddle carrier.

At an automated container terminal AGVs are used for the internal transport. AGVs, see Fig. 6, are robotic vehicles which travel along a predefined path. The road system consists of electric wires in the ground, or a grid of transponders, that control accurately the position of the AGV.

An AGV can carry one 20 feet or one 40 feet container. In the future, Europe Combined Terminals (ECT), in the port of Rotterdam, will use AGVs capable of carrying one 40 feet, one 45 feet or two 20 feet containers. Also, the capacity of the AGV will increase from 40 to 60 tonnes (Cargo Systems, 1999). The front and the back of the AGV are fitted with infrared sensors, which detect obstacles. Further, the area is divided in several subareas, so-called claim areas. While driving, the AGV claims such a claim area and consequently no other AGV can enter this area. Therefore, collisions are avoided. If an AGV hits an obstacle, bumpers on the front and the back of the AGV immediately switch off the motor of the AGV. AGVs are only practical in ports with high labour costs because of the high initial capital costs. In ports with low labour costs, the system of manned vehicles is preferable. At this moment, research is done with respect to a new type of automated vehicle, namely an automated lifting vehicle (ALV). An ALV can lift and transport one container without using a crane.

After the decision which system will be used has been made, one of the problems at the tactical

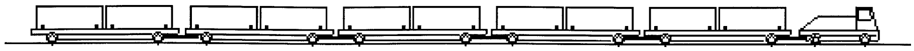

Fig. 5. Multi-trailer system.

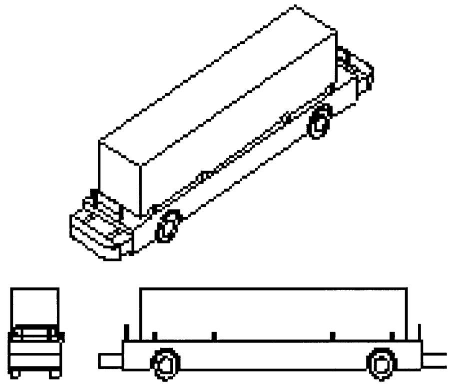

Fig. 6. AGV from different points of view.

level that has to be solved is the determination of the necessary number of transport vehicles. In Steenken (1992) an optimisation system is developed to determine the number of straddle carriers and their route. Because of the fact that the system had to be implemented into a radio data transmission system, the system had to fulfil the conditions of a real-time application. The problem is solved as a linear assignment problem. In Vis et al. (2001) a model and an algorithm are presented to determine the necessary number of AGVs at an automated container terminal. To solve the problem a network formulation is given and a minimum flow, strongly polynomial time algorithm is developed.

At the operational level it should be decided which vehicle transports which container and which route is chosen. A complete review of the routing and scheduling of vehicles in general is given in Bodin et al. (1983). Steenken (1992) and Steenken et al. (1993) describe the more specific problem of the routing of straddle carriers at the container terminal. The objective is to minimise empty-travel distances by combining unloading and loading jobs. Routing and scheduling systems are tested and integrated into a radio data transmission system of a real terminal. Steenken (1992) obtains savings of 13% in empty drives compared with the previously existing situation at the terminal, by solving the problem as a linear assignment problem. Steenken et al. (1993) solve the problem by formulating it as a network problem with minimum costs. Savings of 20–35% in empty-travel distances can be obtained within quite acceptable computation times.

In Kim and Bae (1999) mixed integer linear programming formulations and a heuristic method are given for dispatching containers to AGVs such that the delay of the ship and the total travel time of the AGVs is minimised.

In Chen et al. (1998) an effective dispatching rule is given that assigns AGVs to containers. Other decisions, like determination of a storage location for the import container in the stack, routing of AGVs and traffic control are considered as input. They have developed a greedy algorithm to solve this problem. In the case of a single ship with a single crane, the greedy algorithm is optimal. k AGVs are assigned to the first k containers available. Thereafter, the next container is assigned to the first available AGV. In the case of a single ship with multiple cranes, the greedy algorithm assigns an available AGV to the first available ship crane. Examples can be constructed that demonstrate that the greedy algorithm does not necessarily find the optimal solution in this case. However, with a simulation study it is shown that solutions of the greedy algorithm are close to optimal. Furthermore, the impact of this rule on other decisions, like throughput times of AGVs, crane idle times and number of cranes, is examined. Bish et al. (2001) observe an extension of this problem, namely the problem of dispatching vehicles to containers in combination with the location problem of containers. In other words, in this vehicle-scheduling-location problem each container has to be assigned to a location in the stack (see also Section 2.4) and vehicles have to be dispatched to containers such that the total time to unload all containers from the ship is minimised. It is proven that this is a NP hard problem.

Therefore, in Bish et al. (2001) a heuristic method is proposed to solve this problem. Firstly, an assignment problem is formulated in which containers are assigned to locations by minimising the total distance travelled by vehicles from QCs to locations in the stack. This objective is subject to the fact that each container must be assigned to a location and secondly to the fact that each location cannot be assigned to more than one container. The heuristic method consists of two steps. Firstly, the assignment problem is solved and locations are assigned to the containers based on this solution. Secondly, the greedy algorithm from Chen et al. (1998) is applied to the containers and their locations. The performance of the heuristic is analysed by characterising the absolute and the asymptotic worst-case performance. In the first case the performance is measured by determining the maximum deviation of the heuristic solution from the optimal one for all instances. The asymptotic worst case performance ratio is defined as the maximum deviation from optimality for all sufficiently large instances. It is proved that the worst-case error bounds are tight. To use this effective heuristic in practice other issues, like avoidance of congestion, identifying routes need to be incorporated into the analysis and algorithms.

In Van der Meer (2000) the control of guided vehicles in vehicle based internal transport systems, like container terminals, is studied. Results are presented that show how different vehicle dispatching rules behave in different environments. In Evers and Koppers (1996) the traffic control of large numbers of AGVs is studied. A formal tool to describe traffic infrastructure and its control is developed by using four types of entities: node, track, area and semaphore (i.e. a non-negative integer variable which can be interpreted as free capacity). The tool is evaluated with simulation. It can be concluded that the technique is a powerful tool for modelling transportation infrastructure and its control and that the performance and the capacity of the area increases.

2.4. Stacking of containers

Two ways of storing containers can be distinguished: storing on a chassis and stacking on the ground. With a chassis system each container is individually accessible. With stacking on the ground containers can be piled up, which means that not every container is directly accessible. As a consequence of limited storage space, nowadays stacking on the ground is most common. In this paper, we describe this way of stacking.

The stack (see Fig. 7) is the place where import and export containers can be stored for a certain period. The stack is divided into multiple blocks/lanes, each consisting of a number of rows. The height of stacking varies per terminal between two and eight containers high. At the end of each lane a transfer point is situated. At this point the crane takes/places the container off/on the vehicle that transports the container. Empty containers are usually stored separately. The distribution of empty containers to ports is a related problem. It is for example studied in Crainic et al. (1993), Shen and Khoong (1995) and Cheung and Chen (1998).

A decision at the strategic level that has to be made, is choosing the type of material handling equipment that will take care of the storage and retrieval of containers in and from the stack. Systems like forklift trucks, reach stackers, yard cranes and straddle carriers can be chosen. Yard cranes (see Fig. 8) move on rubber tyres or on rails over the containers. They can provide high density storage and can be automated. These automated cranes are called ASCs. ASCs, see Fig. 8, move on rails and are controlled by the central operating system. The ASC takes/places the container with a spreader from/on the AGV. At the port of Rotterdam, the containers can be stacked six wide and two or three levels high per ASC.

Most of the described terminal operations have their origin and destination at the stack, for example the transport of containers from the stack to the ship. Therefore, efficient stacking is necessary to ensure that the remaining operations can be carried out effectively. The efficiency of stacking depends among other things on the height of stacking and strategies for storage planning of import and export containers. Various storage strategies are described in Chen (1999).

Consequences of higher stacking are reshuffles/rehandles. To reach a specific container it can be necessary to move containers that are placed on

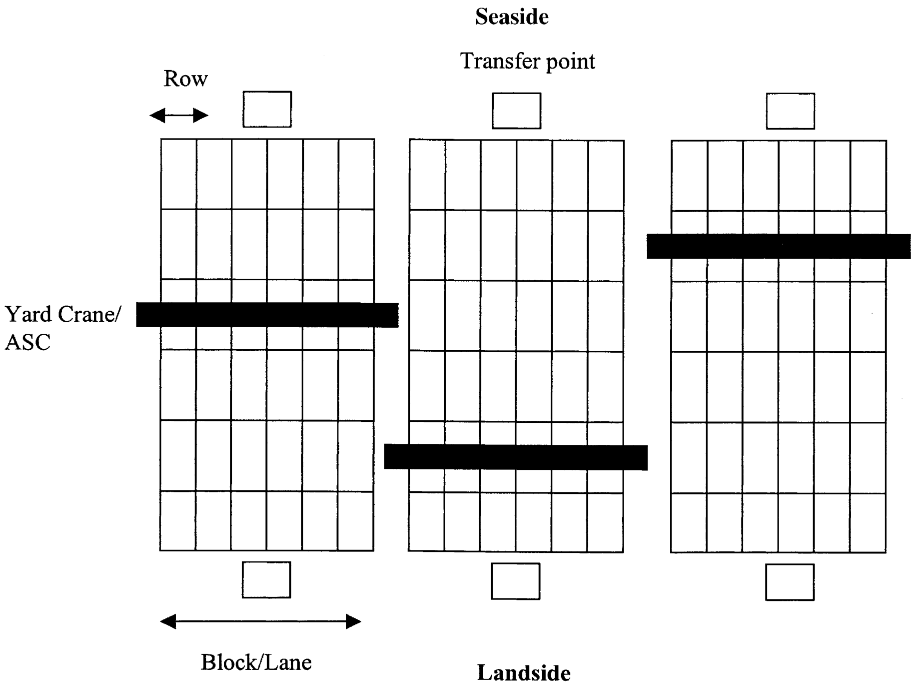

Fig. 7. Schematic top view of the stack.

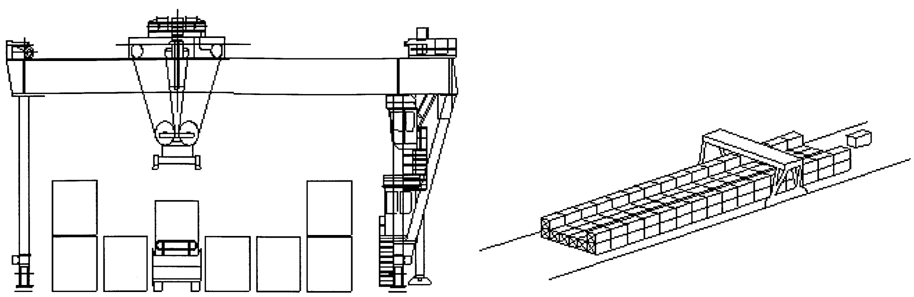

Fig. 8. Yard crane/ASC.

top of the demanded container. To minimise delay by removing containers, reshuffling of the stack can be done in advance. On the other hand, the higher the stacking the less ground space is needed for the same number of containers. In Chen (1999) it is concluded that higher stacking needs the improvement of all the other relevant conditions at the same time to reduce its possible impact. Otherwise, large numbers of unproductive container movements are needed. Chung et al. (1988) develop and test strategies that can reduce the unproductive movements of the stack crane during the loading process and as a result reduce the total container loading time. They propose the idea of using a buffer area where a number of empty chassis are available to store export containers temporarily. A simulation model is developed to investigate the effects of this buffer area on the port's operation. The conclusion is drawn that intermediate storage is effective. On average, 4% reduction in the total loading time can be obtained by using a buffer space. According to the authors, this method can be implemented in every container port.

Obviously, one of the problems at the strategic level is to determine a good stack configuration. De Castilho and Daganzo (1993), conclude that for a good configuration of the stack, methods are needed to estimate the number of moves to retrieve a container as a function of stack height and operation strategy. As a result it is possible to tradeoff extra handling effort for higher stacking against space requirements. Moreover, the best operating strategy can be selected for the chosen configuration. Furthermore, the problem of optimal space allocation is discussed in Holguín-Veras and Jara-Díaz (1999).

In Chen et al. (2000) the storage space allocation problem is examined. A time-space network is developed to assist in assigning containers to storage locations in advance. A time-space network can represent entities moving in time and space. Thereafter, a mathematical programming model can be developed. The objective of this model is to minimise total costs of operation. A test case and a real world case are solved with a branch and bound algorithm.

In Kim and Kim (1999a) the storage space allocation problem is also treated, with decision variables stack height and allocation space. The problem is discussed for import containers with a dynamic space requirement. The objective is to minimise the number of reshuffles under the condition that the space requirements are met. Firstly, the case in which import containers arrive with a constant arrival rate is observed. The stack height and the amount of space are decision variables. It is derived, that the optimal height of the stack equals the total number of import containers during the length of the planning horizon divided by the total number of available locations in the stack.

Secondly, it is assumed that the arrival rate of import containers follows a cyclic pattern with the period of one week. Thirdly, the case in which the arrival rate of containers varies in an irregular way on a rolling horizon is observed. Both problems can be solved by formulating a linear program model. The solution can be obtained by solving the dual problem and related subproblems by applying the subgradient optimisation technique. Summarising, the problem is solved for different cases by determining firstly a formula representing the relationship between the stack height and number of rehandles and secondly by determining methodologies based on Lagrangian relaxation.

In Kim (1997) methods are given for the evaluation of the rehandling of containers, when import containers are picked up in a random way. Methodologies are presented to estimate the expected number of rehandles for the next container to be picked up and the total number of rehandles to pick up all containers. As expected the total number of rehandles increases when the height of the stack increases. The paper only observes the case in which containers for different ships are separated. According to Cao and Uebe (1993) the repositioning of containers is closely related to the p-median transportation problem, namely the transportation problem of containers from rows to be emptied to p rows not to be emptied.

In Taleb-Ibrahimi et al. (1993) results are obtained for long-term and operational planning. They give a description of handling and storage strategies for export containers and quantify their performance according to the amount of space and number of handling moves. At the strategic level the minimum amount of storage space needed is determined. At the operational level the problem of minimising and predicting the amount of work is discussed. Models are given that reflect the relationship between available handling effort, storage space and traffic demand. In Kim et al. (2000) the problem of determining storage locations for export containers with a certain weight is considered. It is required to minimise the expected number of rehandles for the loading of containers on the ship. These rehandles occur for example if lighter containers are stacked on top of heavier containers, which, as assumed in this paper, are needed first in the ship. A dynamic programming model is formulated to solve this problem. For making real time decisions a decision tree is given. The performance of this decision tree is evaluated by comparing its solutions to the solutions of the dynamic programming model. Maximally 5.5% of the decisions made with the decision tree is wrong.

One of the decisions that has to be made at the tactical level is the determination of the number of transfer cranes necessary to ensure an efficient storage and retrieval process. In Kim and Kim (1998) it is discussed how the optimal number of straddle carriers can be determined for import containers. According to the authors, there exists a trade off between the storage density, the accessibility, investment and service to outside trucks. A model is developed to solve analytically this trade off. The sum of all costs is minimised with respect to the number of straddle carriers and amount of space.

If straddle carriers take care of the storage and retrieval of containers from the stack, one of the decisions that has to be made at the operational level is how to route straddle carriers through the stack. In Kim and Kim (1997, 1999b,c) optimal routes of a single crane during loading operations are determined. The container handling time (i.e. the total travel time of the crane) has to be minimised by optimally determining the stack lane sequence and the number of containers to be picked up at each stack lane. The loading schedule has to satisfy the work schedule of the QCs which is assumed to be input. A tour of a crane consists of connected subtours. A subtour is a sequence of stack lanes which are visited by a crane to pick up all containers which will be loaded together at a ship's hold. A tour of a crane can be expressed as a route on a network. In the constructed network the problem is to find a path from the source to the sink and to determine the number of containers to be picked up at each node during the tour (the sum equals the number of containers in the work schedule of the crane) while minimising the travel time. This problem can be formulated as a mixed integer program. The total distance travelled within a lane is constant regardless the loading sequence of containers. Therefore, only the movements between lanes are considered in the total travel distance. With the special structures of this formulation an efficient solution method is developed. This solution algorithm consists of two procedures, namely a procedure to determine basic feasible solutions to the problem of determining the number of containers to be picked up at each lane. Secondly, a dynamic programming procedure is given to determine the route of the crane. Twenty-four problems are tested and it is concluded that the runtime of the algorithm depends highly on the number of combinations of the basic feasible solutions. From the computations it can be concluded that practical problems of a moderate size can be solved by using this algorithm. Kim and Kim (1999d) study the same problem. In this paper the problem is solved by using a beamsearch algorithm. This is a heuristic method for solving large combinatorial problems by efficiently exploring search trees. Each node in this tree represents a partial path from the first partial tour to the current one. Compared to branch and bound methods a beamsearch algorithm rejects unpromising nodes in an aggressive careless manner. The performance of the algorithm is tested by solving 360 sample problems. For small-sized problems the average value of solutions from the heuristic is 114.3% greater than the optimal solution. In both papers, the routing algorithm is only developed for a single crane. To have real practical use, the model should be extended to address multiple cranes.

Another typical problem for a container terminal is that containers have to be stored and retrieved at two sides of the stack (see Figs. 2 and 7), namely seaside (to/from the ship) and landside (to/from other modalities). This is done by the same yard crane/ASC. Some of the decisions that have to be made to ensure an efficient process are: which side has the highest priority and how long can containers wait before they are stored or retrieved.

The problem to decide which ASC carries out which job, can be examined in two ways. If every container is treated as an individual (QC asks for a specific container from the stack), then it is clear which ASC should carry out the job. However, one can also distinguish container categories in a stack. Containers with for example the same destination, the same weight, contents and size belong to the same category. The problem of the packaging of containers is studied in Chen et al. (1995), Davies and Bischoff (1999) and Scheithauer (1999). If the QC asks for a container from a certain category a choice can be made between different containers in different stack lanes taking into account the planned workload of the ASC. The problem when the job should be carried out should be examined at the same moment.

Furthermore, at the operational level a schedule of the order in which containers are retrieved has to be determined. Kozan and Preston (1999) use genetic algorithms as a technique to schedule the retrieval of containers from the stack. The objective is to minimise the time ships spend at the berth for the unloading and loading process. Therefore, they want to minimise the sum of setup times (i.e. the time necessary to retrieve containers from the stack) and travel times (i.e. the time necessary to transport containers from the stack to the ship). The authors suggest that research should be done into the use of other heuristics, like neural networks or tabu search, to see if they are more efficient than genetic algorithms.

2.5. Inter-terminal transport and other modes of transportation

Containers have to be transported from the stack to other modes of transportation, like barges, rail and road. It is expected that, with the growth of terminals in the future, this inter-terminal transport becomes more and more important. According to Van Horssen (1996), new concepts and technologies have to be developed to handle the large numbers of containers expected in the future. Furthermore, research has to be done to the various transport systems by which containers can be transported between the terminals.

This inter-terminal transport can be carried out by vehicles like multi-trailer systems (see Fig. 5) and automated guided vehicles (see Fig. 6). In certain terminals it is possible that containers are put directly on, for example, trains without using transport vehicles.

One of the systems, the multi-trailer system, is studied in Kurstjens et al. (1996). A method is presented that can be used for the planning of the inter-terminal transport. This method is based on a technique which tries to minimise the number of empty trips. To obtain the minimum number of trucks needed an integer linear problem model is developed. For a particular case, it is concluded that the utilisation of the multi-trailer systems can be reduced dramatically. But on the other hand the number of transport vehicles can hardly be reduced.

One way of transporting containers to other destinations is by rail. In Kozan (1997a) an analytically based computer simulation model is developed to describe the container progress at a rail container terminal. Furthermore, the major factors influencing the throughput time of containers, which is a function of cranes, stackers and transfer systems, are discussed. The simulation model is combined with heuristic rules to describe the progress of containers in the system. Firstly, a cyclic heuristic rule is used to assign handling equipment to trains. This rule selects the first available resource beginning with the successor of the last resource seized. As a result, workloads are balanced and utilisation of handling equipment and throughput are higher. Secondly, a new heuristic rule is developed to dispatch trains to tracks. When a train enters the system there may or may not be a queue for the tracks. If there are no free tracks, the train will join the queue. Otherwise, the system sends trains first to track 1 and then to track 2 or 3 if they become available for track 1 and if they minimise total throughput time. In the case that more than one track is used, the train with the fewest number of containers will be unloaded first. A simulation model is developed by using data from a terminal in Australia. Due to cyclic train schedules a weekly simulation period was used. It is concluded, by applying the Wilcoxon Rank Test between the simulation output and the observed data for the total throughput times of containers, that the simulation program imitates the rail terminal effectively. The rail terminal is also a starting point of Bostel and Dejax (1998). They observe the allocation of containers on trains. Different models and solution methods are given and tested on realistic data. It can be concluded that the number of container moves and the use and quantity of equipment can be decreased.

Another way of transporting containers to other destinations is on the road by trucks. In Ballis and Abacoumkin (1996) a simulation model is developed that can be used in the design and evaluation of terminal facilities at the landside. Five heuristics are incorporated in the model to investigate the performance of the system. To obtain a realistic model, experiences of operations managers are included in the model. The comparison between different studies indicates that a shorter truck service time is feasible but that this leads to an increase of traffic conflicts in the internal transport network.

3. Complete container terminals

In Section 2 only problems for individual types of material handling equipment are discussed. Within a container terminal it is obvious that in order to obtain an efficient terminal, it is also necessary to address all problems as a whole. The methods and algorithms obtained by optimising the single processes can be used as a base to the optimisation of the complete terminal. To evaluate control concepts, layouts and material handling equipment, simulation can be used. In a simulation model a real terminal is modelled. For better understanding of all processes and decision making, various experiments with the model should be carried out. By using simulation, it is possible to solve problems that arise simultaneously at several levels and furthermore to investigate results that are obtained by integrating different material systems. On the other hand it is a time-consuming job to develop and validate the model.

In Gambardella et al. (1998) it is shown how operations research techniques can be used to generate resource allocation plans. These plans can be used by terminal managers to determine the best management strategies. Ramani (1996) develops an interactive planning model to analyse container port operations and to support its logistics planning. It is assumed that all unloading operations are completed before loading operations are started. In the simulation model of Yun and Choi (1999) an object-oriented approach is used. The performance of a simple model, in which many design parameters affecting the performance are changed, is observed. Other simulation models for container terminals are developed in Merkuryev et al. (1998).

Instead of the time-consuming simulation models, analytical models can be used. Contrary to simulation models, it is in general, necessary to simplify the problem in such a form that it can be solved. In Van Hee and Wijbrands (1988) a decision support system for the capacity planning of container terminals is developed. Several mathematical models, each describing parts of the complete process, are incorporated in this system. The system can support decisions at the strategic and tactical level. It is not meant for day to day planning. This decision support system is partly based on the system, for a breakbulk terminal, developed by Van Hee et al. (1988).

In Kozan (1997b) analytical and simulation planning models for a complete terminal are compared. It is stated that containers arrive at the seaside in batches, namely on the ship, and not alone. Consequently, a batch-arrival multi-server queuing model is developed and compared with a simulation model. The results of this comparison indicate that, at a 95% level of significance, there exists little difference between the models. However, before implementing the analytical model, long-term data collection is necessary.

In Kozan (2000) the problem is examined of the minimisation of handling and travelling times of import and export containers from the time the ship arrives at the port until the time they are leaving the terminal and vice versa. The complete trajectory that containers go through from the ship to road or rail terminals via storage areas is catched into a network model. Improvements in operational methods are not incorporated in this model. The objective in this model is to minimise total throughput time, which is the sum of handling and travelling times of containers. The model is subject to the following constraints. Firstly, the expected number of containers moved from node i to node j in a time interval is larger than or equal to the minimum amount of containers required in node j within this time interval. Secondly, space constraints at node j should be met. Further, the sum of containers moved to each section of the stack should equal the total number of containers moving into the stack. Also, the sum of containers moved into the stack should equal the sum of containers moved out of the stack. The incoming flow in each node should equal the outgoing flow of containers. Finally, the total number of containers moved should equal the number of containers unloaded from the ship and no more than the maximum number of equipment available is used. It is shown that the expected number of moves per container is the average of the maximum stack height and the minimum stack height. It is explained that this model can be used as decision tool in the context of investment appraisals of multimodal container terminals. Before implementing the model long-term data collection is required.

4. Conclusions and further research

In this paper we have successively described all subprocesses at a manned or automated container terminal and also the planning of the complete terminal. All separate types of material handling equipment and their decision problems at manned container terminals and automated container terminals are discussed. As a result, we have obtained a classification of decision problems at a container terminal. For every decision problem an overview of literature is given. In most cases analytical or simulation models are used to solve the problem.

From examining the literature, it is apparent that, it is in general considered to be necessary to simplify the problem, due to its complexity, before it can be solved by analytical models. Analytical models that are used most often are mathematical programming models, branch and bound models, queueing models, network models and assignment problems. On the other hand, simulation models can be used. In general it is a time-consuming job to develop and validate this kind of models.

In this paper it is shown that already numerous research has been done to solve decision problems at container terminals. However, a number of questions, like the priority planning at the ASC, are still open for research. Furthermore, it is necessary to extend models for simple cases to more realistic situations. For example, the case of routing a single straddle carrier during loading operations should be extended to the case of routing a number of straddle carriers during loading and unloading operations.

Also, the majority of the papers only addresses single types of material handling equipment. In our opinion more attention should be given to the combination of various equipment. For example, the simultaneous scheduling of jobs at ACSs and AGVs. Joint optimisation of several material handling equipment is certainly a topic for future research.

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