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AS/RS based yard and yard planning*

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Abstract: In this paper, we apply the split-platform automated storage/retrieval systems (SP-AS/RSs) (Hu *et al.*, 2005) to store containers in the yard to improve the yard performance and to increase the utilization of the yard space. The layout of an SP-AS/RS based yard is described in detail. To achieve an efficient operation, we present a novel yard space allocation policy called the 'second-carrier-based allocation policy', which can help to alleviate the out-of-sequence problem of containers and the congestion of vehicles at the AS/RS racks. Different allocation policies are compared by an integrated container terminal simulation system. The simulation results show that the second-carrier-based policy is very efficient and has the potential to offer high terminal performance.

Key words: Container terminal, Automated storage/retrieval system (AS/RS), Yard planning, Transportation system
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INTRODUCTION

Maritime container terminals are now facing the challenge of increasing traffic and vessel size. In the past decades, the size and capacity of the container vessels have been increased greatly, but the storage yards in terminals do not change too much and their areas are quite limited. It is the reason that the yards become the critical resources and new equipments and innovative technologies are needed for strengthening the competitiveness of container terminals.

Nowadays, containers are stacked one on top of the other in the stacking yard. Since nothing needs to be built or made, the cost of stacking yard is quite low. However, for retrieving a container, a rehandling operation is needed to remove all others above it in the stack. This operation is unproductive and should be avoided.

Automated storage/retrieval systems (AS/RSs) are capable of providing a random access to all stored items, and are being widely used in the logistics industry (Sarker and Babu, 1995; van den Berg and Gademann, 2000). AS/RS is quite attractive in the application to container terminals due to its high throughput, high space utilization and the ability to eliminate the rehandling operations. Some researches have been exploring the feasibility of implementing AS/RS to store containers. A system called 'Computainer' adopted a multi-story structure and a hoist system to transfer the containers between a truck and an AS/RS rack cell (Ioannou *et al*., 2002). Liu *et al*.(2002) presented four different automated container terminal concepts, including AS/RS. Ho and Chen (2006) compared the AS/RS based container terminal with other container terminal designs. To further improve AS/RS's throughput and flexibility as it is deployed to the yard, we proposed a novel design called 'split-platform AS/RS' (SP-AS/RS for short) for container storing (Hu *et al*., 2005).

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As yard performance has great impact on the overall throughput of a terminal, an efficient yard planning is quite important. There is quite a lot of research in this area. McDowell *et al*.(1985) developed a mathematical model to determine the stacking configuration after analyzing the container handling operation. Chung *et al*.(1988) developed and tested the strategies that could reduce the unproductive movements of the stacker crane. Watanabe (1991) provided a simple method for estimating the number of rehandling operations. de Castilho and Daganzo (1993) gave the general expressions for the expected number of handling efforts to retrieve one container from a storage stack under the segregation and non-segregation storage policies. Taleb-Ibrahimi *et al*.(1993) proposed the storage policies for the local export containers. Kim (1997) presented several tables and equations to estimate the number of rehandling operations for the next pick-up. Kim and Kim (1999) derived a formula representing the relationship between the stack height and the number of rehandling operations. To increase the land utilization of the yard, Chen (1999) compared various storage strategies. Kim *et al*.(2000) and Kim and Park (2003) proposed some programming models to address the problem of yard space allocation. Zhang *et al*.(2003) used a rolling horizon approach to address the same problem. Fu *et al*.(2007) reduced the problem of space allocation to a 2D packing problem with a time dimension. Han *et al*.(2008) proposed a mixed integer programming model to determine the storage locations of incoming containers.

Till now, to the best of our knowledge, there is no research for applying SP-AS/RS to the container terminals. In this paper, we present a yard plan for the SP-AS/RS based yard and build a simulation model called ‘high capacity terminal simulation system’ (HCTS for short) to evaluate our design.

SP-AS/RS BASED STORAGE YARD

Design of SP-AS/RS (Hu *et al*., 2005)

The innovation of SP-AS/RS lies in the novel design of the storage/retrieval machine (SRM), which has separate horizontal and vertical movement mechanisms. This design is to increase the throughput and carrying capacity of AS/RS. With the new SRM, SP-AS/RS can handle extra large and heavy sea containers. The structure of SP-AS/RS is illustrated in Fig.1. For more details about the structure and operation of SP-AS/RS, interested readers are referred to (Hu *et al*., 2005).

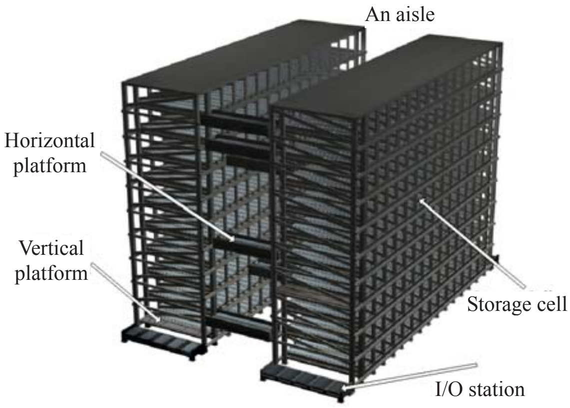

Fig.1 Structure of the split-platform AS/RS (Hu *et al*., 2005)

Compared with an AS/RS using conventional SRM, the SP-AS/RS has many advantages, including the ability of handling heavier loads at a higher speed, higher performance and better tolerance of faults (Hu *et al*., 2005).

In the container terminal application, when a container is to be taken to a vessel by a truck, it will be first transferred from its storage location to the horizontal platform (HP) on the corresponding tier. The HP then moves to the first bay of the rack to transfer the container to the vertical platform (VP). After that, the VP goes down to the first tier with the container and transfers it to the I/O station. A yard crane is responsible for picking up the container on the I/O station and putting it on the truck.

Different types of AS/RS racks

To accommodate the different sizes of containers, we designed three different types of AS/RS racks as shown in Fig.2. A 20-foot rack can only hold 20-foot containers, and a 40-foot rack is for storing 40-foot containers. Each cell inside a mixed rack can store either one 40-foot container or two 20-foot containers. The use of mixed racks provides the flexibility to cope with the capacity demand by 20- or 40-foot containers at peak hours.

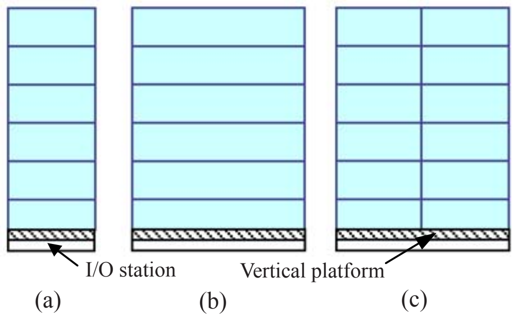

Fig.2 Schematic view of the three types of AS/RS racks (top view). (a) A 20-foot rack; (b) A 40-foot rack; (c) A mixed rack

Different types of racks can be connected flexibly according to different yard operation practice. Fig.3 shows some of the rack configurations in HCTS, and the letter inside a rack denotes the rack type. In Fig.3a, two 40-foot storage units (one storage unit refers to two SP-AS/RS racks in an aisle, as shown in Fig.1) are placed side by side in the middle and one 20-foot storage unit is located at each end. Fig.3b shows one 40-foot storage unit in the middle and two 20-foot storage units at its each side. In Fig.3c, there are four mixed racks in the middle, which are connected by one 20-foot HP and two 40-foot HPs. Thus, both 20- and 40-foot containers can be stored to (retrieved from) the mixed racks. This configuration demonstrates the flexibility of the yard layout when SP-AS/RS is applied.

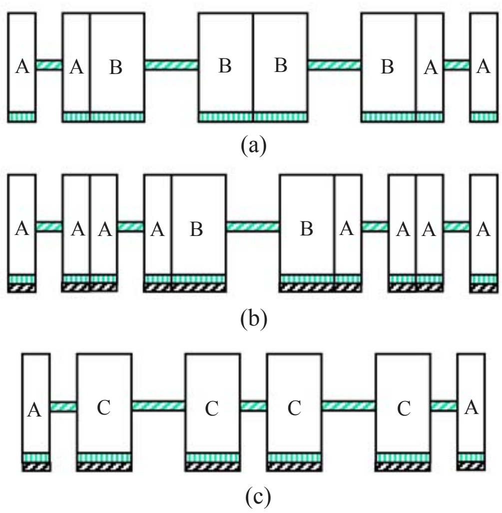

Fig.3 Three types of AS/RS rack connections (top view). The letters 'A', 'B' and 'C' represent a 20-foot rack, a 40-foot rack and a mixed rack, respectively

Yard layout

Similar to a conventional yard, the ground space of an SP-AS/RS based yard is partitioned into many rectangular blocks to place AS/RS racks. These storage blocks are separated by the traffic lanes for vehicles. Fig.4 shows how the yard space is partitioned into blocks, and Fig.5 shows how a block is divided into sections. In Block 1, the AS/RS rack connection shown in Fig.3a is adopted. The connection type in Fig.3b is used for the racks in Block 3. The storage cells in these two blocks are dedicated to storing 20- or 40-foot containers. Mixed racks are placed in Block 2 with the connection shown in Fig.3c. Since the racks in Block 1 to Block 3 are using different types of connections, we group them together and call this combination a 'block group'. In this way, the total yard can be divided into several block groups, and each block group contains three blocks.

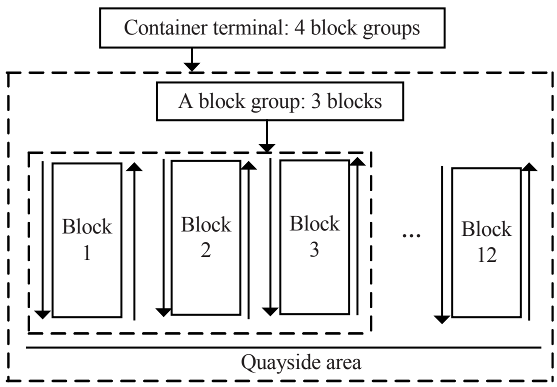

Fig.4 Layout of an SP-AS/RS based yard

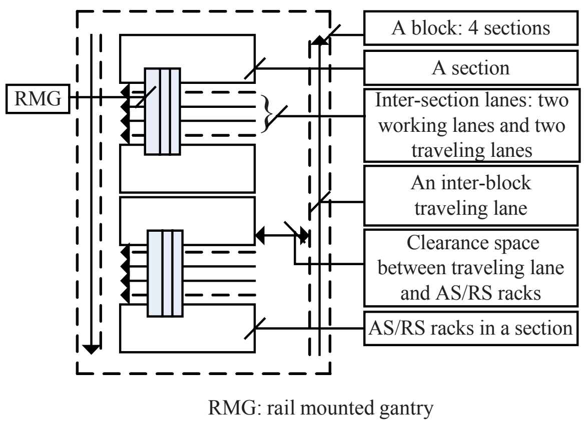

Fig.5 Structure of a block in an SP-AS/RS based yard

Fig.6 provides a snapshot of an SP-AS/RS based yard in HCTS. The block groups and blocks are labeled.

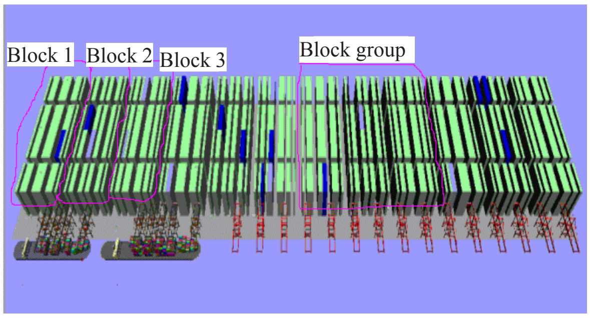

Fig.6 Snapshot of an SP-AS/RS based yard

Interface between SP-AS/RS and the transport system

The working lanes and traveling lanes have been shown in Fig.5. When a truck arrives at the I/O station of an AS/RS rack, it will be served by an RMG (rail mounted gantry). Fig.7 shows a snapshot.

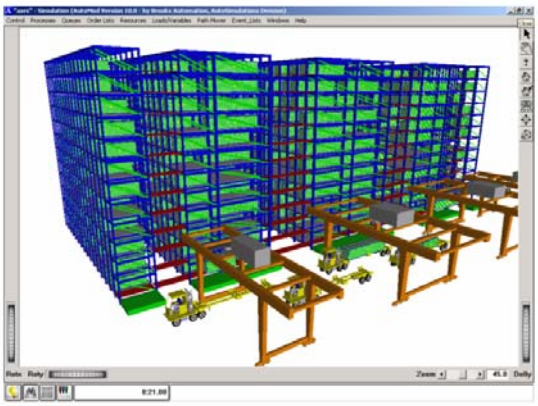

Fig.7 Snapshot of the interface between SP-AS/RS and the transport system

If a truck comes to an AS/RS rack to deliver a container, the RMG will pick up the container from the truck and put it on the I/O station. The truck may go for the next job while the container stays at the I/O station waiting for being transferred to its destination cell by the vertical and horizontal platforms. If the truck comes for a container, it has to wait until the platforms move the container onto the I/O station. The container is then put on the truck by the RMG.

SPACE ALLOCATION POLICIES

Yard space allocation is one of the intractable issues in the container terminals. One reason is that normally only local information is available when allocating yard space to the containers. Another reason is the interleaving operations of loading and unloading in the yard. Lack of yard space also interferes the execution of some allocation policies, and the uncertainties (e.g., congestion) of the transport system bring more difficulties to this issue. Due to these factors, manual interference exists in allocating storage space to containers. To design suitable allocation policies for the SP-AS/RS based yard, we refer to the guidelines from practice of the conventional yard.

Randomized allocation policy

The idea of randomized allocation policy is quite natural. It spreads the containers evenly in the yard to prevent the congestion of vehicles. Before a vessel's berthing, a suitable AS/RS cell is randomly chosen for each of the containers to be put into the yard. The same rules are applied to local import containers.

In HCTS, the yard planner follows the following steps to allocate an AS/RS cell for a 20-foot container:

(1) Randomly choose a 20-foot rack which still has empty cells, and then randomly choose a cell inside the rack;

(2) If the above operation is impossible as all the 20-foot racks are full, first randomly choose a mixed rack which has empty cells, and then randomly choose an empty 20-foot cell for this container;

(3) If still no empty cell can be found, report 'yard is full'.

In the case of allocating a cell for a 40-foot container, the process is similar.

However, by analyzing the performance of HCTS using the randomized yard space allocation policy, several disadvantages were discovered. One is the out-of-sequence problem which occurs during the loading operation. When the yard storage locations for the containers in the same loading list are too scattered, these containers may not be able to reach the quay crane (QC) in the correct order, which is very important for the correct operation of a QC. For example, the containers to be loaded first are quite far away from the quayside, but the containers very near the QC should be loaded later. Since there is much less distance for the latter containers to reach the QC, it is quite likely for them to arrive earlier than the former ones. The out-of-sequence problem can cause traffic congestion at the quayside and lower the QC performance.

The other problem is that sometimes there is contention for the same AS/RS I/O station among different vehicles. If the consecutive containers in a job list are allocated to the same AS/RS rack, the vehicles handling them have to go to the same rack one by one. Sometimes, these vehicles may reach the rack at almost the same time due to the different travel time delays. If the I/O station is still serving another vehicle when a new vehicle arrives, the new comer has no choice but to wait. In this case, not only the throughput of the transport system will be lowered, but also other problems such as parking lots for the waiting vehicles have to be solved.

Second-carrier-based allocation policy

To solve these problems, the second-carrier-based allocation policy is proposed. The second carrier means the vessel into which the discharged transshipment containers will be loaded. The idea of the second-carrier-based allocation policy comes from the concept of 'cluster yard'. Based on this concept, the containers are allocated according to their second carriers. The basic rules for the second-carrier-based allocation policy are as follows:

(1) The containers to be loaded onto the same second carrier should be stored in the AS/RS racks relatively close to each other.

This rule helps to solve the out-of-sequence problem. An allocation window is used to localize the racks for one second carrier. Fig.8 provides an illustration of the idea of an allocation window. H_i, H_j and V_i, V_j are the horizontal and vertical coordinates to bound the window, respectively. The size and position of an allocation window are decided according to the number of containers to be loaded onto the second carrier and its possible future berthing location. At the same time, the number of free storage cells in the window is also a factor to be considered when the size of the window is determined.

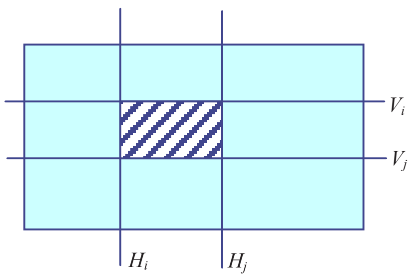

Fig.8 Illustration of the idea of an allocation window. H_i, H_j and V_i, V_j are the horizontal and vertical coordinates to bound the window, respectively

(2) As the QC used in HCTS works four times faster than a yard crane, at least four yard cranes are needed to serve one QC. To reduce the congestion in the yard, preferably the yard cranes are chosen from different yard blocks.

(3) The actual number of the racks reserved for a QC depends on the number of containers to be loaded. These racks will be assigned to the containers in the loading list of the QC in a round-robin fashion according to the loading sequence.

Fig.9 illustrates this method. For example, Racks 1 to 4 serve the same QC. The containers numbered 1, 5, 9, … in the QC's loading list will be assigned to Rack 1, and the containers numbered 2, 6, 10, … will be allocated to Rack 2, and so on. This kind of assignment can alleviate the vehicles' contention for the same AS/RS I/O station.

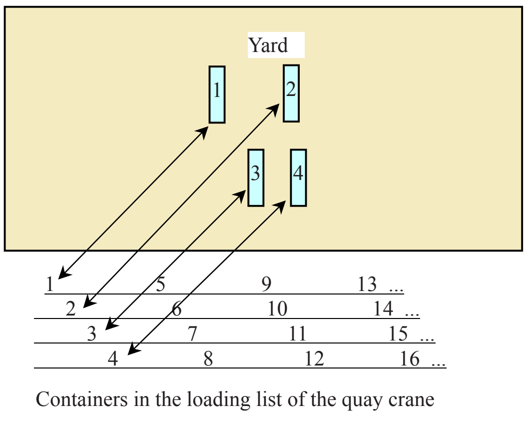

Fig.9 Round-robin fashion of assigning racks

(4) The local import containers are assigned to outer racks to prevent the local hauliers' vehicles from going into the inner yard, which may lead to the traffic overlap between the hauliers' vehicles and the lateral transport system.

EVALUATION OF YARD SPACE ALLOCATION POLICIES

In HCTS, the QC rate is used as a performance indicator to evaluate different yard space allocation policies. In this preliminary evaluation, we conduct four experiments by using different job lists for a mega vessel. A mega vessel is chosen because the allocation policy should be efficient in handing smaller vessels if it can satisfy the turn-around time of a mega vessel.

In the experiments, there are 384 SP-AS/RS racks in the yard, and each rack has 14 bays and 12 tires. The number of yard cranes is 240. The technical parameters related with the SP-AS/RS and yard crane are listed in Tables 1 and 2. The workload distribution used in the experiments is listed in Table 3. All QCs are assigned even workload.

The comparisons of the system performance between the second-carrier-based allocation policy and the randomized allocation policy are shown in Table 4. The system performance is improved by 16.4% on average when the second-carrier-based allocation policy is used, showing that this policy is more effective.

Table 1 Velocity of the platforms of SP-AS/RS

Platform	Velocity (m/s)	Acceleration/deceleration (m/s^2)
HP	2	0.3
VP	1	0.3

Table 2 Parameters of the yard crane

Parameter	Value
Hoisting speed	1 m/s
Trolley speed	1.17 m/s
Trolley acceleration/deceleration	0.2 m/s^2
Mean of aiming time	1.5 s
Standard deviation of aiming time	5 s

Table 3 Workload distribution

Job list	Number of quay cranes	Number of containers unloaded	Number of containers loaded
1	8	7776	7615
2	8	8539	7012
3	8	7939	7102
4	7	8539	7012

Table 4 Performance comparisons between different yard space allocation policies

Job list	Yard allocation policy	Quay crane rate (moves/hour)									Improvement* (%)
		QC1	QC2	QC3	QC4	QC5	QC6	QC7	QC8	Average	
1	S	51	49	50	50	49	49	49	49	49.5	15.1
	R	46	40	41	42	45	40	45	45	43.0	
2	S	51	49	50	50	49	50	49	50	49.8	17.5
	R	46	41	42	41	42	41	44	42	42.4	
3	S	51	50	50	50	50	49	49	50	49.9	17.4
	R	43	42	42	42	42	42	46	41	42.5	
4	S	51	50	51	50	51	49	50	NA	50.3	15.4
	R	46	41	45	45	41	45	42	NA	43.6	

S: second-carrier-based allocation policy; R: randomized allocation policy. * Refers to the improvement in the average quay crane rate achieved by the second-carrier-based allocation policy compared to the randomized allocation policy

CONCLUSION

The yard operation is an important part of the container terminal operations. To improve the performance of the yard, the SP-AS/RSs are introduced into the yard for storing containers. With the use of them, the unproductive rehandling operations can be eliminated and the space utilization can be increased.

The yard space allocation policy can greatly influence the performance of the entire terminal. In this paper, two allocation policies, namely the 'randomized allocation policy' and the 'second-carrier-based allocation policy' are discussed in detail. The experimental results show that the second-carrier-based policy is quite efficient.

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