Estimating the space requirement for outbound container inventories in port container terminals

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Abstract

This paper proposes a method for allocating storage space to groups of outbound containers in port container terminals. For this allocation, a collection of adjacent stacks is reserved for each group of containers with the same attributes. The impacts of various space-reservation strategies on the productivity of the loading operation for outbound containers are discussed. A method is suggested for determining the size of the space requirement for outbound container yards.

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1. Introduction

Operations in port container terminals consist of: the discharging operation, during which containers are unloaded from ships; the loading operation, during which containers are loaded onto ships; the delivery operation, during which inbound containers are transferred from the marshalling yard to road trucks; and the receiving operation for outbound containers from road trucks. From the perspective of customer service, the turnaround time of container-ships must be minimized by increasing the speed of ship operation; further, the turnaround time of road trucks must be kept as small as possible.

In container terminals, the loading operation for outbound containers is carefully pre-planned by load planners. For load planning, the concerned container-ship agent usually transfers a stowage plan to the terminal operating company several days before the ship's arrival. In the load profile, each slot is assigned with a container group, which is identified by the port of destination (POD) and the size of the container to be stowed into the slot.

A slot of a ship may be filled with any container as long as the container group specified for that slot is the same as the group of the container. Therefore, the handling effort in the marshalling yard can be reduced by optimally assigning outbound containers to slots and sequencing them for the loading operation. In the decision process, load planners usually attempt to minimize the handling effort for quay cranes and yard equipment at the same time. The output of this decision-making is called the “load sequence list.” For an efficient load sequence, outbound containers need be laid out in optimal locations. Fig. 1 (Park, 2003) shows a stowage plan. It shows slots into which containers of two groups (defined by size and destination port) are assigned.

For efficiency in loading, several principles are widely accepted for space planning. The first principle is that yard-bays that are assigned to a container-ship should be located as near as possible to the berthing position of the corresponding ship (the Nearest Location Principle). The second principle is that containers must be located so as to avoid interference between yard cranes during the ship operation (the Least Congestion Principle). Thus, containers that are bound for the same vessel are distributed over several blocks.

The third principle is that containers of the same group must be located close to each other, i.e., in either the same bay or adjacent bays (the Concentrated Location Principle). This is a well-known principle for container handling systems that consist of yard cranes, yard trucks, and storage blocks that are laid out parallel to the quay. This type of handling system is popular in Asian countries. During the loading operations of containers, containers of the same group are likely to be loaded onto slots that are located close together, as illustrated in Fig. 1. Thus, they are usually loaded consecutively during the loading operation. As a result, the travel distance of yard cranes can be reduced by placing containers of the same group in slots that are close to each other. In practice, all the stacks in a yard-bay or in adjacent yard-bays are usually allocated to a container group. Further, since the outbound containers randomly arrive at the yard, such an allocation must be performed in advance, as shown in Fig. 2. In this paper, a set of adjacent stacks, which is allocated to the same container group is called a “cluster.” The block in Fig. 2(a) has four clusters. The determination of the reservation (cluster) size of a container group is the main focus of Sections 2–4.

The fourth principle is that containers must be located so as to minimize relocations of containers (the Least Relocation Principle).
Principle). Thus, containers of different groups must not be mixed in the same stack. Otherwise, relocations may occur for picking up a container of a group that is located under containers of other groups. We assume that this principle is applied in all the cases in this paper.

For space allocation, yard planners usually consider the four principles introduced above. Among these four principles, the concentrated location principle and the least relocation principle are related to the space requirement, which is the main focus of this study.

Regarding the space allocation for outbound containers, Taleb-Ibrahimi et al. (1993) have suggested a space allocation strategy in which temporary storage areas are provided for containers that arrive before a designated storage space has been allocated for them. The time to allocate designated space to each vessel is determined using a trade-off between the cost of the temporary storage space and the cost of relocating the containers from the temporary storage area to the designated space. Kim and Park (2003) proposed a dynamic method for space allocation for outbound containers in which the space in each block is allocated to each vessel for future container arrivals. Zhang et al. (2003) addressed a similar space allocation problem. They attempted to balance the workload among different blocks to avoid possible bottlenecks in terminal operations.

Lim and Xu (2006) addressed the problem of locating the reserved space for each group of containers in a block. They proposed a method for scheduling the allocation of empty spaces to each group so that in the final layout, the reserved spaces for the same group are located adjacent to each other.

Lee et al. (2006) proposed a yard-space allocation method for a transshipment hub port. They suggested an algorithm for assigning parts of blocks (called the sub-blocks) to containers that are to be loaded (discharged) onto (from) a vessel so as to minimize congestion during the discharging and the loading operations. Lee and Hsu (2007) addressed the problem of pre-marshalling outbound containers for speeding up the loading operation. Bazzazi et al. (2008) also addressed the space allocation problem and attempted to minimize the variation in the handling workload across various blocks. For locating containers, Dekker et al. (2006) introduced various algorithms that are useful for automated container yards and compared them in terms of performance. Cordeau et al. (2007) proposed a method for assigning storage spaces to vessels for minimizing container rehandling operations in the yard in a transshipment container terminal.

Kim and Kim (1999) and Narasimhan and Palekar (2002) addressed the problem of determining the visitation sequence for a single yard-crane (YC) with respect to yard-bays and the number of containers to pick up during each visit (to a yard-bay).

The main contributions of this paper are as follows:

1. This paper discusses how to determine the amounts of space allocations (reservations), while prior studies have assumed that the amounts of space allocated are given and proposed methods for determining the locations of the space allocations (Kim and Park, 2003; Zhang et al., 2003; Lee et al., 2006; Lim and Xu, 2006; Bazzazi et al., 2008).

2. This paper analyzes the impact of the size of space reservations on the efficiency of loading operations. To the best of the authors’ knowledge, this is the first such attempt in the open literature.

3. This study proposes a method for determining the total space requirement of the outbound container yard by considering not only the space for reservation but also the fluctuation in the container inventory level. Again, to the best of the authors’ knowledge, this is the first such attempt in the open literature.

The next section introduces the space reservation and its relationship with the loading operation. Section 3 proposes a mathematical model for allocating the space for reservation across different container groups so that the number of reservations (clusters) can be minimized. Section 4 proposes several different space allocation rules and evaluates the performance of the rules through a simulation study. Section 5 provides formulas for estimating the space requirement for different arrival patterns of vessels and compositions of container groups. The last section summarizes the contribution of the paper and suggests directions for further research.

2. Space reservation and space requirement

A container yard for outbound containers is usually divided into several blocks, each of which consists of 20–30 yard-bays. Each yard-bay consists of between six and eight stacks in the case of the yard-crane (YC) system. Fig. 2 illustrates a block with 10 yard-bays and a yard-bay with six stacks of four tiers.

When a container of a group arrives at the yard and finds no empty slot in the area that is reserved for that container group, a new area must be selected. To obey the Concentrated Location Principle, a space that consists of a yard-bay or multiple adjacent stacks must be selected for stacking the arriving container and reserving the remaining slots for future arrivals of containers in the same group. To obey the Least Relocation Principle, all slots in the same stack must be reserved for containers of the same group. Owing to this manner of reservation, additional empty spaces are required in addition to the space for stacked containers. This is why the two principles are related to the space requirement. Fig. 2 illustrates a block in which some slots are already occupied by containers and others are reserved for some groups of outbound containers.

Fig. 3 illustrates how the loading operations are carried out. The numbers in the stowage plan (Fig. 3(a)) represent the sequence for loading containers into slots, while the numbers in the yard map (Fig. 3(b)) represent the pickup sequence for containers from the yard-bay. Since containers in the same group are picked up consecutively, as shown in Fig. 3(b), the travel distance of yard cranes may be reduced by locating containers of the same group in adjacent stacks.

Fig. 4(a) shows the cumulative inventory changes of containers in a group. The upper curve represents the cumulative reservation curve of the group. The lower curve corresponds to the
cumulative arrival of containers in the group. The difference between the cumulative reservation and cumulative arrival corresponds to the reserved slots for the container group. When the space requirement for outbound containers is estimated, not only the inventory of containers but also the space for reservation must be considered.

For the outbound container yard in a terminal, Fig. 4(b) shows: the cumulative space supply arising from the departure of vessels, \( s(t) \); the cumulative space reservation, \( r(t) \); and the cumulative arrival of containers, \( a(t) \). The amount is expressed in twenty-foot equivalent units (TEUs). Note that the cumulative amount of space and the cumulative number of container arrivals can be estimated from the historical data or the data supplied by shipping liners. Then, the gap between the curves, \( r(t) - a(t) \), corresponds to the space that is constantly available for use towards reservations in the terminal.

Slots in a cluster are usually reserved together when the space is reserved. When the storage spaces are reserved more frequently, the average size of clusters becomes smaller. The smaller the average size of clusters is, the smaller the space requirement for reservation (SRR) becomes, which is represented by \( r(t) - a(t) \) in Fig. 4(b).

Fig. 5 shows that when a larger space is provided for reservation (SRR), the number of clusters decreases. SSR represents the additional space that is provided for reservation beyond the cumulative arrival of outbound containers, which is expressed by a percentage of the cumulative arrival of outbound containers. The curve in Fig. 5 was obtained from a simulation study.

In Fig. 6, the abscissa indicates the average number of clusters for each group and the ordinate shows the average completion time for the entire loading operation of a vessel. The graph in Fig. 6 implies that the average completion time of the loading operation for a vessel increases, as the average number of clusters per group increases. The graph was drawn from schedules of the loading operation for different sets of stowage plans and yard maps, which were constructed by using the load scheduling algorithm of Jung and Kim (2006). The values on the curve correspond to the average makespan over 10 problems that feature a specific number of clusters per container group.

Sections 3 and 4 discuss how to minimize the number of clusters (space reservations). Also, Section 5 proposes a method for estimating the space requirement for outbound containers by considering the optimal sizes of clusters.

3. Minimizing the number of space reservations under a limited available space for reservation

In the centralized storage policy, the stacks that are allocated to a container group are located in adjacent positions. By minimizing the number of space reservations, we can minimize the number of clusters for each container group, which means that the completion time of the loading operation is minimized as per the assertions in Fig. 6.

Suppose that the outbound containers of \( n \) groups are arriving at the yard. Let the arrival rate per unit time of the containers of group \( i \) be \( r_i \). Also, suppose that a certain amount of space is reserved for containers of group \( i \) that arrive during the time period, \( t_i \). Then, the minimum number of slots to be reserved for group \( i \) at the beginning of \( t_i \) should be \( r_i t_i / 2 \). The larger the \( t_i \), the more the adjacent stacks should be allocated to the container group, \( i \). The average number of reserved empty slots for group \( i \) during \( t_i \) becomes \( r_i t_i / 2 \).

For minimizing the number of space reservations, which means the number of clusters of containers of the same group, the objective function of the problem becomes \( \sum_{i=1}^{n} \frac{1}{t_i} \). Since the available space for reservation is limited, a constraint, \( \sum_{i=1}^{n} \frac{r_i t_i}{2} \leq s \), is added to the formulation. Thus, the formulation of the problem becomes

\[
\text{Min } \sum_{i=1}^{n} \frac{1}{t_i}
\]

subject to

\[
\sum_{i=1}^{n} \frac{r_i t_i}{2} \leq s,
\]

\[
t_i > 0.
\]

To solve the above problem, constraint (2) is relaxed. Then, the formulation becomes:

\[
\text{Min } \sum_{i=1}^{n} \frac{1}{t_i} + \lambda \left( \sum_{i=1}^{n} (r_i t_i - 2s) \right)
\]

subject to \( t_i > 0 \) and \( \lambda \geq 0 \).

The first-order differentiation of (4) with respect to \( t_i \) results in

\[
-\frac{1}{t_i^2} + \lambda r_i = 0,
\]

which yields

\[
t_i' = \sqrt{\frac{1}{2r_i}}.
\]

The first-order differentiation of (4) with respect to \( \lambda \) results in

\[
\sum_{i=1}^{n} r_i t_i = 2s.
\]

By using Eq. (5), Eq. (6) becomes

\[
\sum_{i=1}^{n} \frac{r_i}{2r_i} = 2s.
\]
which can be changed into

\[ \frac{1}{\sqrt{2}} \sum_{i=1}^{n} \sqrt{t_i} = 2s. \]

Thus,

\[ z^* = \left( \frac{1}{2s} \sum_{i=1}^{n} \sqrt{t_i} \right)^2. \]

Further,

\[ t_i^* = \frac{2s}{\sqrt{\frac{1}{2s} \sum_{i=1}^{n} \sqrt{t_i}}} = 1 / \sqrt{t_k}. \]

If \( t_i \) is restricted to have only integral values, then the objective values at \( t_i^* \) and \( t_i^* + 1 \) can be compared with each other for choosing the one with the lower objective value, which stems from the convexity of (4).

4. Comparing various reservation rules

This paper assumes that containers that are bound for different vessels cannot be stacked in the same yard-bay. When a container arrives at the yard and cannot find a reserved space for the corresponding container group, a set of adjacent empty stacks (cluster) is newly reserved for the group.

We propose the following four differing rules for determining the number of stacks for the reservation of storage space:

1. Fixed space rule (FSR): a fixed number of stacks are reserved for each container group.
2. Fixed period rule (FPR): the length of the period that is to be covered by one-time reservation is fixed. We reserve empty stacks by the same amount as required for receiving containers that arrive during the period of fixed length.
3. Arrival rate rule (ARR): empty stacks are reserved in proportion to the arrival rates of containers of the various groups. Thus, the number of stacks to reserve for a group is determined by multiplying the average arrival rate of containers for the corresponding group by a constant value, \( a \).
4. Square root of arrival rate rule (SRAR): empty stacks are reserved in proportion to the square roots of the arrival rates of containers of the respective groups. This rule is based on the result of the previous section (refer the expression in (8)). Thus, the number of stacks to reserve for a group is determined by multiplying the square root of the average arrival rate of containers for the corresponding group by a constant value, \( \beta \).

The average arrival rate is the estimated number of containers that arrive at the yard during a certain length of time in the immediate future. In the simulation studies, we used the next 24 h for calculating the average arrival rate. A simulation study was conducted to test the performance of the four rules for allocating space. The following assumptions were employed in the simulation study:

1. forty vessels visit the port at equal time-interval \( (1.13 \text{ days}) \) during the simulation. All the vessels are homogeneous in that they have the same total number of outbound containers, the same number of container groups (eight), and the same number of containers in each group. (However, the number of containers can vary across groups);
2. the arrival of outbound containers is modeled by using an empirical distribution of the arrival times of containers collected from the Busan Eastern container terminal during June through August in 2004. Discharging containers are not considered;
3. the total available storage space is assumed to be 125% of the maximum number of containers (in TEUs) that are stacked in the yard during the simulation period; and
4. the simulation is run 10 times for each set of parameters.

The simulation was conducted by using eM-plant on a Pentium IV (RAM-512 Mb) PC. During the simulation, a storage space is assigned to an arriving container via the following procedure:

Step 1: find an empty slot in a non-empty stack that is reserved for the same group as that of the arriving container. If there is such a slot, then store the arriving container into that slot. Otherwise, go to Step 2;
Step 2: find an empty stack that is reserved for the same group as that of the arriving container. If there is such a stack, then store the arriving container into that stack. Otherwise, go to Step 3;
Step 3: if there is an area with empty and non-reserved stacks, then select the area with the largest number of such stacks. The number of reserved stacks will be the minimum of (i) the number of available adjacent stacks in the selected area, and (ii) the number of stacks as calculated by one of the four rules. Stack the arriving container into one of the newly reserved stacks. If there are no empty and non-reserved stacks, then go to Step 4; and
Step 4: find an arbitrary empty stack and store the arriving container onto the stack. If there is no empty stack, then the container is classified as having no assignable space.

For finding the best values of the parameters for each rule, simulation studies were conducted for different values of the parameters for each rule. Fig. 7 shows the change in the average number of clusters per vessel for different numbers of reserved stacks per reservation in FSR. The average number of clusters per vessel is the smallest when the number of reserved stacks per reservation is four. Note that the average number of clusters per vessel increases again when the number of reserved stacks per reservation exceeds four. When the latter increases, the space requirement for reservation increases. This results in more frequent shortages in the empty space for reservation. Thus, the arriving containers more frequently come to occupy the area that is reserved for other container groups. As a result, this increases the average number of clusters per vessel.

For the case of FPR, a similar simulation study was conducted. Fig. 8 shows the result of the simulation experiment and illustrates that the number of clusters is minimized when the space is reserved for container arrivals during the next 56 h. Figs. 9 and 10 also show the results of the simulation study for the case of ARR and SRAR. When the values of the multiplier \((a\) and \(\beta\)) are 2.5 and 6.5, respectively, the average number of clusters per vessel is the smallest.
Fig. 11 shows how the average size of reservations (clusters) changes as the loading operation is about to commence. For FSR, the average size of reserved clusters does not change because the reservation size is fixed by the definition of the rule. Since the number of arrivals of containers increases rapidly as the commencement of the loading operation nears, the average size of reservations also increases rapidly for the cases of FPR and ARR. However, the rate of increase is lower for the case of SRAR than for the cases of FPR and ARR.

Fig. 12 shows the changes in the average number of clusters per vessel for different inter-arrival times of vessels. As the average inter-arrival time increases, the space requirement becomes lower and as a result, the average size of reservations per vessel becomes larger. The average number of clusters varied with the reservation rule. Among the four rules, FSR yielded the largest number, while SRAR yielded the smallest average number of clusters. Since the completion time is expected to be shorter for a smaller number of clusters, it can be said that SRAR is the best rule among the four rules. Thus, SRAR was used in the subsequent experiments.

5. Estimating storage space requirement for outbound containers

This section assumes that SRAR is used to determine the size of reservations, that is, the space reservation for a group of containers is proportional to the square root of the arrival rate of outbound containers in that group. However, the reservation parameter, $\beta$, must be determined considering the limitation in the storage space of the terminal.

This section assumes that the arrival rate of outbound containers at the terminal is constant during the arrival period. Two models are considered with regard to the arrival of vessels and the number of outbound containers per vessel.

(1) Constant inter-arrival time of vessels and irregular number of containers (CVIC). The vessels arrive at the terminal at constant time-intervals but the number of outbound containers may differ across vessels.

(2) Irregular inter-arrival time of vessels and irregular number of containers (IVIC). Unlike the case of CVIC, the inter-arrival time between vessels does not remain the same. Note that IVIC is a more general case than CVIC.

Fig. 13 illustrates the curves for the space requirement, including the container inventory and reservation, for a container group or vessel. The amount of reserved space is $\frac{4\sqrt{2\pi}}{3}$ for container group $k$ of vessel $i$ and $\frac{4\sqrt{\pi}}{3}$ for vessel $i$. Note that $r_i$ and $r_{ik}$ are the arrival rates of containers for vessel $i$ and group $k$ of vessel $i$, respectively.
the space requirements of vessels at time $t$

The total space requirement is the sum of the individual curves of the shape shown in Fig. 13. Since the maximum of the total space requirement can be found at one of the points where the slope changes from a positive to a negative value, the curve reaches at its maximum at one of the points where the curves of the shape shown in Fig. 13. Since the maximum of the total space requirement will attain its maximum value when $t = a_i$.

Then, we know that the maximum total space requirement follows

$$N \left( E \left[ \sum_{j \in S_k} f_j(d_k) \right] , \ Var \left[ \sum_{j \in S_k} f_j(d_k) \right] \right).$$

where

$$E \left[ \sum_{j \in S_k} f_j(d_k) \right] = \sum_{j \in S_k} E[X_j] p_j(d_k),$$

and

$$\text{Var} \left[ \sum_{j \in S_k} f_j(d_k) \right] = \sum_{j \in S_k} \text{Var}[X_j] p_j^2(d_k).$$

We define the service level of the space as the probability that the supplied space satisfies the maximum total space requirement and denote it by $\gamma$. Then, the amount of space to be supplied for outbound containers can be expressed as follows:

$$\sum_{j \in S_k} E[X_j] p_j(d_k) + z_{1-\gamma} \sqrt{\sum_{j \in S_k} \text{Var}[X_j] p_j^2(d_k)}.$$ (10)

5.1. Numerical examples

This section provides an example for the case of CVIC. We collected real-world data from the Pusan Newport Co., Ltd. The average values were calculated for the number of loading containers, the inter-arrival time of vessels, the operation time of vessels, the number of destination ports (POD) per vessel, etc. There were 14 service lanes and each service lane had one vessel each week on average. Therefore, we used the following simplifying assumptions and input data (based on the practical data) in the estimation of the space requirements.

(1) The same 14 vessels repeatedly arrive at the port.
(2) Both the number of PODs and the number of groups are 7.

### Table 1

<table>
<thead>
<tr>
<th>Service lane</th>
<th>Mean (TEU)</th>
<th>S.D (TEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane 1</td>
<td>328</td>
<td>111</td>
</tr>
<tr>
<td>Lane 2</td>
<td>340</td>
<td>249</td>
</tr>
<tr>
<td>Lane 3</td>
<td>1171</td>
<td>279</td>
</tr>
<tr>
<td>Lane 4</td>
<td>569</td>
<td>219</td>
</tr>
<tr>
<td>Lane 5</td>
<td>1537</td>
<td>285</td>
</tr>
<tr>
<td>Lane 6</td>
<td>926</td>
<td>464</td>
</tr>
<tr>
<td>Lane 7</td>
<td>491</td>
<td>255</td>
</tr>
<tr>
<td>Lane 8</td>
<td>577</td>
<td>335</td>
</tr>
<tr>
<td>Lane 9</td>
<td>937</td>
<td>245</td>
</tr>
<tr>
<td>Lane 10</td>
<td>2160</td>
<td>974</td>
</tr>
<tr>
<td>Lane 11</td>
<td>444</td>
<td>142</td>
</tr>
<tr>
<td>Lane 12</td>
<td>433</td>
<td>100</td>
</tr>
<tr>
<td>Lane 13</td>
<td>1436</td>
<td>240</td>
</tr>
<tr>
<td>Lane 14</td>
<td>1352</td>
<td>465</td>
</tr>
</tbody>
</table>
The inter-arrival time of vessels and the operation time of the storage space. This study introduces the concept of the utilization of the storage space is 80%. Therefore, 4680 stacks were bays, 9 rows, and 5 tiers. It is believed that the maximum containers, which corresponds to 13 blocks. Each block has 50 stacks.

The value of \( \beta \) was set to 6.5, which was the result of Fig. 10. The inter-arrival time of vessels and the operation time of vessels are the same for all vessels, that is, 10.42 and 11.16 h, respectively.

\[ (c_j - b_i) = 36 \text{ and } (b_i - a_i) = 240 \text{ h}. \]

The basic unit of the storage space is a stack and each stack has five tiers.

The average number (TEUs) of loading containers and the standard deviations for each service lane are as shown in Table 1.

By using the model of CVIC, we estimated the space requirement at every \( a_i, b_i, \) and \( c_i \) for each vessel and found that the largest total space requirement (including the space for reservation) occurred at \( t = c_{30} \), when the total number of stacks required was 3176 as shown in Table 2. Note that for this evaluation, we used the average value of the number of containers (TEUs) for each lane.

However, when we considered the distribution of the number of containers (TEUs) for each lane, the amount of space to be supplied for outbound containers could be evaluated as follows:

\[
\sum_{j \leq 30} E[X_j] p_j(c_9) + z_{1-0.1} \sqrt{\sum_{j \leq 30} \text{Var}[X_j] p_j^2(c_9) - 4422(\text{stacks})},
\]

which is 40% larger than the corresponding requirement under the assumption of deterministic numbers of containers for each lane. Here, the service level was assumed to be 90%, which is the probability that the maximum total space requirement will be larger than the calculated amount of space (TEUs), viz., 4422 stacks.

The PNC container terminal uses 31% of the yard for outbound containers, which corresponds to 13 blocks. Each block has 50 bays, 9 rows, and 5 tiers. It is believed that the maximum utilization of the storage space is 80%. Therefore, 4680 stacks were being used for outbound containers in the PNC terminal at the time of the survey, which is similar to the result in this paper.

### 6. Conclusions

This paper addresses a method for determining the size of the storage space for outbound containers in the initial stage of constructing container terminals or re-constructing existing terminals. In practice, simple formulas are used to determine the size of the storage space. This study introduces the concept of reservation space, which is being used in practice, for locating the containers of the same group close to each other. This strategy of space allocation is for speeding up the loading operation for outbound containers.

Various rules were proposed for determining the optimal reservation sizes. Through a simulation study, the rules were compared with each other in terms of their performance. It was found that the square root arrival rate rule (SRAR) was the best among the four proposed rules. SRAR reserves empty stacks for a container group in proportion to the square root of the arrival rate of containers in that group. Also, some analytic expressions were provided for estimating the space requirement for outbound containers under various simplifying assumptions.

This study used a simplified simulation model for evaluating the performance of various reservation rules. A more detailed simulation model needs to be developed to investigate the impact of different reservation rules and values of parameters of each rule. The method for estimating the space requirement is still based on the enumeration of possible candidate values of the space requirement. A simpler estimator needs to be developed by using statistical analysis.

### Acknowledgement

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (The Regional Research Universities Program/Institute of Logistics Information Technology).

### References


