An Investigation into Effectiveness of Container Arrangements on Optimizing a Containership Stowage Plan

NGUYEN Thanh Thuy*, Etsuko NISHIMURA** and Akio IMAI**

Abstract

Container is a standard in worldwide transportation method, which is capable of being moved by sea, road or rail with relative simplicity. Due to the continuously increasing container trade, many container terminals as well as liner shipping companies are presently frustrating to shorten the turnaround time of a ship for financial savings. Therefore, any methods to improve the containership stowage process would be significant. This paper examines the effectiveness of container arrangements in order to evaluate how to optimize the stowage plan, which was established at the present port and associated with the unloading plan at next port. The efficient of the ship stowage plan is evaluated by the minimum number of rehandled container required and the maximum value of ship stability obtained during to trip from the present port to the next port. The genetic algorithm is employed as a heuristic for the approximately optimized solutions and the validation of the proposed approach is performed with some computational experiments.

Keywords: Containership handling; Container Terminal; Genetic Algorithm; Logistics

1. Introduction

Shipping transportations are heterogeneous, distributed, complex, dynamic, and large which require cutting edge technology to yield extensibility and efficiency. Competition among container ports continues to increase as the worldwide container trade grows rapidly (Ryan, 1998). Managers in many container ports are trying to attract more container shipping lines by automating the handling of equipments, providing and speeding up various port related services as well as handling processes. One of the important applications in a container terminal is how to arrange containers on yards, which produces various numbers of stowage plans for the ship and affect to the high productivity of the terminal.

This paper examines the effectiveness of container arrangements on container yards (CYs) and on board a ship in order to evaluate how to optimize the stowage plan, which is established at the present port and associated with the unloading plan at next coming port, as shown in Fig. 1. As being presented in Thuy et al. (2008), the efficiency of the loading process at the present port depends on the number of redundant repositioning activities when loading containers from yards onto the ship. In a loading sequence, if the target container is stacked below others, which are to be pickup later, in a container block on a yard because of the ship's balance and other reasons, then the loading task requires the so-called "loading rehandle" in order to remove and reposition the others. As an extended study from the formulation and heuristics applied in Thuy et al. (2008), this study deals with another type of "rehandle" as well, called "unloading rehandle", which occurs when moving containers on board that are not destined for being discharged at a particular port in order to reach the others that are unloaded at that port. This is likely to take place when containers destined for a specific port are spread out over several ship holds, being associated with the ship routine and different types of container on board.

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Fig. 1. Ship stowage planning process

In this study, the efficiency of the ship stowage plan is evaluated by the minimum number of container rehandles required and the maximum value of ship stability obtained during to trip from the present port to the next port.

2. Literature review

Studies on container handling efficiency for optimal stowage plan can be classified in three distinct albeit interlinked categories. One category deals with the scheduling problem for handling equipment such as quay cranes, transfer cranes and straddle carriers. Another category concerns the analysis of trade-offs between yard storage area and container handling efficiency. The last category considers the minimum rehandles during the handling sequences.

Some studies have been conducted on the effectiveness of container volumes, container density on yard blocks, container arrangements, etc., to the ship loading plan. Kim (1998) figured out the evaluation of number of rehandles on different configurations of container stacks. Chen et al. (2000) carried out statistical analyses on the relationship between container rehandles, container handling volume and storage density on a yard. Imai et al. (2002) conducted an investigation of container stack complexity and number of rehandles taken in loading process. Imai et al. (2006) carried out the solutions of stowage plan obtained with different container arrangements on yards and on board for the loading task.

3. Problem assumptions

The study is carried out based on the following simplifications and assumptions, which bring this study to be more practical and applicable:

(a) Some containers have already been stowed on board of the ship before loading containers in question.
(b) Only standard containers are considered in this study. They have exterior dimensions conforming to ISO standards of 20 ft and 40 ft long, 8 ft 6 in. high and 8 ft deep.
(c) Transfer crane system (Rubber Tired Gantry Crane-RTG or Rail Mounted Gantry Crane-RMG) is considered throughout this study.
(d) GM, which is the distance between the gravity center and metacenter, is used as the ship stability factor in this study. In practice, other two stability factors are taken into consideration: heel and trim. However, stability issues caused by those two factors can be dealt with by using ballast; therefore they are not considered in this study.
(e) Each container has the same center of gravity, i.e., the weight is imposed at the center of container along three axes. Therefore, containers have their overall center of gravity at their middle location.

4. Problem modeling

4.1. Loading rehandle formulation

Resembling Thuy et al. (2008), the estimated number of loading rehandles is utilized in order to take the rehandle objective into account in the formulation. The loading rehandle is estimated based on the expected number of rehandles when retrieving each container in a block as the first one to be taken.

The model of loading rehandles objective is presented as follows:

\[ \text{Minimize } \sum_{i \in P} \sum_{j \in S} \sum_{k \in K} (1 - \frac{j - 1}{B - 1}) R_k x_{ijk} \]  \hspace{1cm} (1)

Subject to

\[ \sum_{i \in P} \sum_{j \in S} x_{ijk} \leq 1 \quad \forall k \in K \]  \hspace{1cm} (2)

\[ \sum_{i \in P} \sum_{k \in K} x_{ijk} = 1 \quad \forall j \in S \]  \hspace{1cm} (3)

\[ \sum_{j \in S} \sum_{k \in K} x_{ijk} = 1 \quad \forall i \in P \]  \hspace{1cm} (4)

\[ x_{ijk} \in \{0, 1\} \]  \hspace{1cm} (5)

where

\( B \): the number of loaded containers in the CYs

\( P \): set of position of loaded containers in CYs
S: set of loading order and available positions on ship bays

K: set of number of assigned quay cranes (QCs) or yard cranes (YCs)

RLij: number of containers to be rehandled when a container at location i of yard bays is picked up as the first container in the loading sequence

\( x_{ijk} = \begin{cases} 1 & \text{if the container at position i of yard bays is loaded as the } j^{th} \text{ container by crane } k \text{ in the loading sequence} \\ 0 & \text{otherwise} \end{cases} \)

Objective (1) is the minimization of the total number of loading related rehandles that should be taken in loading sequences. Constraints (2), (3) and (4) ensure that every container is loaded with any order of loading sequence.

Assignment of corresponding slots of ship bays with different container sizes

The ship holds consist of some even bays or contiguous odd bays used for stowage container of 40' or 20'. Consequently, if a 40' container is stowed in an even bay (for instance bay 22 in Fig. 2), the location of the same row and tier corresponding to two contiguous odd bays (e.g. bay 21 and 23 in Fig. 2) are no longer available for stowing container of 20'. Moreover, for safety reason, 20' containers cannot be stacked above 40' containers and both 20' and 40' containers cannot be stacked above empty cells.

In a loading sequence, containers are loaded from the quay side to the sea side, bay by bay and filled to each corresponding empty slot, called "Available corresponding slot". In each ship hold, each even bay b corresponds to two contiguous odd bays \( b_a(n=1, 2) \). Therefore the position of a slot can be defined by \( s(b,r,t) \) for container of 40' or \( s_q(b_a, r, t) \) with \( n=1, 2 \) for container of 20', in which \( b, r, t \) are number of bay, row, tier of a slot, respectively.

Fig. 2 shows an example of how to assign containers in different sizes to the available slots in ship holds. In the left side of Fig. 2, there are 12 containers with different sizes of 20' and 40' on yards, while the right side is available slots in ship holds, in which even bay 22 is for 40' containers and two contiguous odd bays 21 and 23 are for 20' containers. The number on each container shows the order of loading sequence. For random arrangement in ship holds, the containers are assigned into ship slots as follows:

**Step 1:** With the container \( j=1 \), the size of \( j=1 \) is 20', therefore we check all available slots the odd bays 21 (n=1) and 23 (n=2) from tier 1, row 1.

**Step 2:** There are three available slots in lowest tier (tier 1), which are (21,4,1), (22,4,1) and (22,5,1)

**Step 3:** Assign container \( j=1 \) to the slot (21,4,1) and go to container \( j=2 \)

**Step 4:** Container \( j=2 \) is a 40', thus the lowest available corresponding slots in the even bay 22 are (22,3,2) and (22,6,2). Assign \( j=2 \) to slot (22,3,2)

**Step 5:** With \( j=3 \) (20' container), the lowest available corresponding slots are (23,4,1), (23,5,1). Assign container \( j=3 \) to slot (23,4,1)
Step6: Continue assigning other containers with the same rules: Container $j=4$ to $(22,6,2); j=5$ to $(22,3,3); j=6$ to $(23,5,1); j=7$ to $(21,4,2); j=8$ to $(21,5,2); j=9$ to $(23,4,2); j=10$ to $(23,5,2); j=11$ to $(22,6,3)$ and $j=12$ to $(21,4,3)$

For the destination arrangement in ship holds, first we split the number of containers on CYs $(P)$ and number of available positions on ship $(S)$ into $p$ subsets $P_p$ and $S_p$, $p=1,...,\psi$ where $\psi$ is the number of different ports visited by the ship. Next we applied the above procedure to assign containers destined for port $p$ to each subset of slots $S_p$.

4.2 Unloading rehandle formulation

The stowage plan at previous ports determines the unloading sequence at present and subsequent ports. When unloading containers, there are accordingly movements from the upper to lower located one. Therefore the rehandle takes place only when containers not intended for unloading are located vertically between or on top of containers to be unloaded. Essentially the former containers are called blocking containers, which necessitate rehandle. However, obviously blocking containers are not rehandled when no containers under them are unloaded. Consequently the total number of rehandled containers in unloading sequence is obtained by subtracting the number of unblocking containers from the total of potentially blocking containers. Since the number of unloading rehandles does not depend on the number of crane assignment, it is not necessary to consider to number of unloading cranes in this section.

Let us label $S_L^b$ and $S_E^b$ sets of even bay and contiguous odd bays of containers which are already stowed onboard before the loading sequence.

$S_L^b$ and $S_E^b$ are sets of even bays and contiguous odd bay of containers which are loaded during loading sequence.

The sets of even bays and total contiguous odd bays of ship holds where containers are located are $S^b = S_L^b \cup S_E^b$ and $S^b = S_E^b \cup S_E^b$, respectively.

$y_n^b$ and $y_n^b$ are positions of containers in location $l$ and $l'$ at a specific row $r$ of even bay $b$ and odd bay $b_n$ of ship holds, respectively. $y_n^b=1$ and $y_n^b=1$ if the container in positions $l$ and $l'$ are unloaded at port, and $=0$ otherwise.

To compute the number of rehandled containers at a specific row $r$ of even bay $b$ or contiguous odd bays $b_n$, we define auxiliary variables:

$N_r^b, N_n^b$: The lowest tier position of unloaded container at row $r$ of the even bay $b$ and contiguous odd bay $b_n$.

Model of total number unloading rehandles is formulated as follows:

[PU]

Minimize

\[
\{ \sum \sum \sum \sum \lambda_{brc}\mathbf{1}(1-y_{n}^{b}) - \sum \sum \lambda_{brc}(U_{r}^{b} - N_{r}^{b}) \} + \\]

\[
\{ \sum \sum \sum \sum \sigma_{abn}^{b}(1-y_{n}^{b}) - \sum \sum \sigma_{abn}^{b}(U_{r}^{b} - N_{r}^{b}) \} \]

subject to

$U_{r}^{b} \leq T_{n}^{b} y_{n}^{b} \quad \forall r \in S^b$ \hspace{1cm} (8)

$y_{n}^{b} = \{0,1\} \quad \forall l \in r, r \in b; b \in S^b$ \hspace{1cm} (13)

where

$T_{bl}$, $T_{bf}$: The tier positions of container located in position $l$ and $l'$ onboard and is predefined in the problem.

$\lambda_{r}^{b} = 1$ if $N_{r}^{b} > U_{r}^{b}$ ($\forall n = 1,2$); $=0$ otherwise

$\eta_{r}^{b} = 1$ if $N_{r}^{b} < U_{r}^{b}$ ($\forall n = 1,2; U_{r}^{b} \neq 0$)

or $U_{r}^{b} = 0$ ($n = 1,2$); $=0$ otherwise

$\sigma_{r}^{b} = 1$ if $N_{r}^{b} \neq 0$ and $U_{r}^{b} \neq 0$, $\forall n = 1,2$; $=0$ otherwise
Constrains (8), (9) and (10), (11) define the auxiliary variables \( U_r^b, U_r^{b^*} \) and \( N_r^b, N_r^{b^*} \), respectively.

In order to justify the objective (7), small examples are taken as shown in Fig. 3, which depicts three different ship rows: 4, 5 and 6 of the even ship bay 22, the contiguous odd bays 21 and 23. Computations for those rows (referred to as cases 1, 2 and 3, respectively) are shown in Table 1.

### 4.3. Ship stability evaluation

As being presented in Thuy et al. (2008), ship stability is evaluated by three factors in those the most important factor is GM which is the distance between the center of gravity (G) and the metacenter (M).

GM is calculated by the following equation:

\[
GM = G_0M + \frac{\sum_{i} L_iW_i}{SD + CB + \sum_{i} W_i} 
\]

where

- \( L_i \): distance between the metacenter of ship and the container location \( j \) onboard ship where container \( i \) is loaded
- \( W_i \): weight of container \( i \)
- \( SD \): ship’s displacement without cargo
- \( CB \): weight of containers already on board before loading sequence
- \( G_0M \): distance between the center of gravity of ship \((G_0)\) and the metacenter \((M)\)

To formulate the loading sequence, the GM contribution ratio is defined as \( GM_{ik} \) for the container at location \( i \) on yard bay picked up and stored at cell position \( j \) on ship bay by crane \( k \). Therefore, the formulation with the maximization of GM can be defined as follows:

Maximize

\[
\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} GM_{ik}x_{ik} 
\]

Subject to (2) – (5);

\[
\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} GM_{ik}x_{ik} \geq gm \quad (16)
\]

\[
\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} GM_{ik}x_{ik} \leq Gm \quad (17)
\]

where \( gm \) and \( Gm \) is the minimum and maximum GM.
guaranteed, respectively.

4.4. Problem model
Among a number of techniques for generating a non-inferior solution set, we employ the weighed sum of objective function method (Collette and Siarry, 2003). In this method, the problem is defined as a mathematical programming model with incorporated some objectives. In our study, we have three objectives [PL], [PU] and [PG], in those [PL] and [PU] are not in conflict since they both convey the number of rehandles of different handling sequences. Therefore, we can comprise them in one objective of minimization of rehandles. Putting this comprised objective and the objective of maximization of GM into one single objective with weights, the final single objective problem is defined as follows:

\[
\begin{align*}
\text{Minimize} & \quad \sum \sum (1 - \frac{j}{B - 1}) w_{jk} + \\
& \quad \left\{ \sum \sum \sum \xi (1 - y_{jk}) - \sum \sum \eta (1 - y_{jk}) \right\} + \\
& \quad \left\{ \sum \sum \sum \gamma (1 - y_{jk}) - \sum \sum \sum \sigma (U - N) \right\} \\
\text{Subject to} & \quad (2) - (5), (8) - (14), (16), (17)
\end{align*}
\]

In objective (18), \( w_1 \) and \( w_2 \) are weights of the rehandles and GM objectives, in which \( w_2 \) is set negative because of the maximization of the GM while \( w_1 \) is positive because of minimization of number of rehandles.

\[
\begin{align*}
& w_1 - w_2 = 1 \\
& w_1 \leq 1 \\
& |w_2| \leq 1
\end{align*}
\]

5. Genetic Algorithms
5.1. Outline of the solution procedure
GAs represent a powerful and robust approach for the developing heuristics for large scale combination optimization problems. Each feasible solution of a problem is treated as an individual whose fitness is governed by the corresponding objective function value. A GA maintains a population of feasible solutions (also know as chromosomes) on which the concept of the survival of the fitness, among structure, is applied. There is a structured yet randomized information exchange between two individuals (crossover operator) to give rise to better individual. Diversity is added to the population by randomly changing some genes (mutation operator). A GA repeatedly applies these processes until the population converges.

5.2. Representation
In developed GA application, the container positions on the yard are selected to establish the chromosomes, associated with the order of loading sequence. Fig. 4 shows an example of typical chromosome representation for one handling crane. The length of the string digits modifies the positions of containers on yard plus number of cranes minus one. Therefore, it consists of some parts connected by zero, each of which represents the positions and handling order of each crane in loading sequence.

5.3. Fitness
A fitness value reflects the goodness of an individual, compared with the other individuals in the populations. In this study, because of the minimization problem, the smaller the objective function is, the higher fitness value must be.

<table>
<thead>
<tr>
<th>Cell #</th>
<th>1</th>
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<th>3</th>
<th>4</th>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td><strong>Chromosome</strong> (positions on CYs)</td>
<td>57</td>
<td>52</td>
<td>49</td>
<td>50</td>
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<td>61</td>
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<tr>
<td>Ship even bay #</td>
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<tr>
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Fig. 4 Chromosome Representation for number of quay cranes = 1
Considering some alternative fitness functions, the sigmoid functions, defined in equation (22), is found to be better where \( y(x) \) denotes the objective function value.

\[
f(x) = 1/(1 + \exp(y(x)/10,000))
\]  

(22)

5.4. Genetic algorithm operators

Reproduction is a process where individual chromosomes are copies according to their scaled fitness function value.

Two sophisticated selection schemes are tested to pick up superior individuals from the remainders: Roulette-wheel selection and Tournament selection. According to the preliminary computational tests, the former is chosen since giving better results. For crossover procedure, after two types of crossover operator are tested by number of experiments, the so-called two-point crossover is employed. The mutation rate was chosen at 0.08 since it produced better results.

6. Numerical experiments

The data to be used for the analysis are the container loading information observed in Port of Kobe. The input data include number of cranes, container volumes, types, weights and locations in yard stacks and in ship holds on board of three ships, each with a capacity of 800, 1600 and 2400 TEUs.

The objective function coefficients \( w_1 \) and \( w_2 \) of the weighting method basically vary by the interval of 0.05.

In this statistics, some containers on each ship were not to be handled at Kobe; therefore, these were not included in the analysis. The metacenter positions of the ships are not known and therefore they are all assumed to be located at the upper deck level.

On the yard, containers are arranged in blocks, each block including the maximum of 20 bays and each bay containing the maximum of 6 rows and 4 containers height. Table 2 shows the container characteristics of all case studies, in which two container volumes are considered: 256 and 512 containers. Each volume has both 20' and 40' containers.

An analysis is made with 20 sets of container stacks with the same stack density per each container volume (256 containers/384 slots and 512 containers/768 slots) given by a uniform random distribution. Table 3 implies the ship sizes, number of QCs and YCs being used as well as the types of container arrangement on CYs and in ship holds. The solution procedures were coded in "C++" language and all computer experiments have been performed on a PC Pentium IV. For each case, five stack arrangements (SA) were selected by uniform random number method. Three weight levels and three destinations are assumed. The maximum GM guaranteed of 1.45m and the minimum one of 0.95m is selected.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Container characteristics of case studies</th>
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<td>( n ) (containers)</td>
<td>TEU</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>256</td>
<td>348</td>
</tr>
<tr>
<td>512</td>
<td>667</td>
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<table>
<thead>
<tr>
<th>Table 3</th>
<th>Characteristics of ships, CYs arrangements, QCs and TCs</th>
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<tr>
<td>Containers</td>
<td>Ship sizes</td>
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<tr>
<td>256</td>
<td>800 TEUs</td>
</tr>
<tr>
<td></td>
<td>1600 TEUs</td>
</tr>
<tr>
<td></td>
<td>2400 TEUs</td>
</tr>
<tr>
<td>512</td>
<td>800 TEUs</td>
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<td></td>
<td>1600 TEUs</td>
</tr>
<tr>
<td></td>
<td>2400 TEUs</td>
</tr>
</tbody>
</table>
First of all, we examines the cases of containers arranged on CYs by random, by weight and by destination while the containers in ship holds are arranged by random, for instance the case of loading 256 containers onto the 800TEU ship with random ship hold arrangement as shown in Fig. 5 (by random on CYs), Fig. 6 (by weight on CYs) and Fig. 7 (by destination on CYs).

In term of rehandles, when containers on CYs are arranged by destination as in Fig. 7, the handling sequence produces a smaller number of rehandles than two other cases, while the largest number of rehandles is obtained when containers on CYs are arranged by weight as in Fig. 6. In contrast in term of GM, the maximum GM value is yielded for case of weight arrangement on CYs whereas the minimum GM value obtained in case of destination arrangement on CYs.
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The next cases are considered with ship hold arrangements by destination though containers on CYs still are arranged by random, by weight and by destination, respectively to Fig. 8, Fig. 9 and Fig. 10. As being shown in those figures, the same trend exists in both terms of number of rehandles RH and ship stability GM.

In Fig. 9, the container arrangement by weight on CYs produces a larger number of rehandles but smaller values of GM than the other CYs arrangements illustrated in Fig. 8 and Fig. 10.

The container arrangement by destination on CYs, presented in Fig. 10, takes advantage in term of rehandles but disadvantage in term of GM values. Comparing the results between random ship hold
arrangement and destination ship hold arrangement, ones with destination arrangement, in general, cause a lot of rehandled movements.

This observation is resulted from the comparison between Fig. 5 and Fig. 8 and the one between Fig. 6 and Fig. 9. It is naturally presumed that if a specific ship hold is exclusively dedicated to a destination, retrieving containers from yard stacks results in enormous troublesome due to strict restrictions to the order of loading containers from the yard to ship in order to maximize the GM.

Notice that this trend does not happen in Fig. 10, since both yard stacks and ship holds are arranged by destination and therefore the set of containers in one yard stack moved as a whole the ship regardless of ship hold arrangement.

Next, the cases of larger container volume of 512 containers being loaded onto the 2400 TEU ship are studied. Fig. 11, Fig. 12 and Fig. 13 show the cases of containers in CYs are arranged by random, by weight and by destination whilst containers in ship hold are arranged by random. Fig. 14, Fig. 15 and Fig. 16 show the cases of containers in CYs are arranged by random, by weight and by destination whilst the containers in ship holds are arranged by destination.

Comparing to small cargo cases, the large cargo cases have a similar feature in terms of rehandle, that is both the yard stack and ship hold arrangements by destination reveals the minimum number of rehandle. The large cargo volume cases show that yard arrangement by weight comes to a large GM. It seems normal, since the yard stack by weight likely facilitate smooth container retrieve in loading sequence with less rehandles to provide a large GM.

In term of rehandles, container arrangement on CYs by weight causes more rehandles than two other ones, in spite of the smooth container retrieve in loading sequence. The main reason is a big number of unloading rehandles happened in the associated unloading sequence in the next coming port of the ship routine.

Comparing between the ship hold arrangements by random and by destination, the formal issues a better GM than the later in both cases of small and big container volumes.

7. Conclusions
This paper presented an investigation into effectiveness of container arrangements on optimizing a containership stowage plan. The proposed solution method has good performances in terms of solution quality. In particular, the most important consideration about the performance is the possibility of finding stowage plans for maximizing the terminal productivity as well as keeping good ship stability for ship's sail performance. Moreover, our study enables the handling operations of each portion of the ship to be performed in parallel thus minimizing the turnaround time of the containership and hence improving the whole performance of maritime terminals.

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References
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Questions and answers
Saburo TSURUTA (Tokyo University of Marine Science and Technology)

How much time can you improve loading and unloading time comparing similar former research results?

NGUYEN Thanh Thuy

Thank you for your question

Even though this study does not mention to the handling time but the efficiency of the container arrangements to the ship stowage plans, the handling time can be calculated and compared based on the results of our previous study Thuy et al (2008), as follows:

(1) There is no similar research which considering to the ship stowage plan in both loading and unloading sequences, therefore we can only compare the loading time:

In Sciomachen and Tanfani (2007), loading time for 100 containers with the number of QCs =2 is 2.23.34 (h.m.s), while in Thuy et al (2008) loading time suggestion for 114 containers with the same number of QCs is 1.57.32 (h.m.s)

(2) Comparing between the actual handling situation of 256 containers in Kobe Container Terminal and the results obtained by this research without considering to the time-risk-factor, the solution of this method is about 18 minutes faster than the actual one.