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Multi-objective simultaneous stowage and load planning for a container ship with container rehandle in yard stacks

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Abstract

The efficiency of a maritime container terminal primarily depends on the smooth and orderly process of handling containers, especially during the ship's loading process. The stowage and associated loading plans are mainly determined by two criteria: ship stability and the minimum number of container rehandles required. The latter is based on the fact that most container ships have a cellular structure and that export containers are piled up in a yard. These two basic criteria are often in conflict. This paper is concerned with the ship's container stowage and loading plans that satisfy these two criteria. The GM, list and trim are taken into account for the stability measurements. The problem is formulated as a multi-objective integer programming. In order to obtain a set of noninferior solutions of the problem, the weighting method is employed. A wide variety of numerical experiments demonstrated that solutions by this formulation are useful and applicable in practice.
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1. Introduction

The overwhelming majority of general cargo is nowadays containerized. As the containerized transportation system is capital-intensive, the fast ship turnaround at a container terminal is essential for the economic performance of liner shipping companies. The turnaround time of a ship includes the time for berthing, unloading, loading and departure, and therefore it can be stated that container loading and unloading are critical elements of the efficiency of this transport chain. Ship operators as well as port managers are keen in

determining the optimal vessel stowage and associated loading plans, which minimize ship's dwell time in port with acceptable ship stability.

In a cellular containership, if specific containers (referred to as *target containers*) must be stowed at vertically middle locations in a ship's hold for stability reasons, they have to be loaded in a loading sequence after the containers that are to be stowed below them and before the containers that are to be stowed above them. Concurrently, another restriction emerges during the picking of containers from a yard to be loaded onto the ship, since containers are piled up to form block formations on the yard for storage purposes. If the target containers are stacked on the yard below others, which are to be picked up later, then the loading task requires the so-called "*loading-related rehandle*" in order to remove and reposition the others. This is very likely to occur, as detailed information about the order of the loading sequence is not available when containers begin to arrive at the terminal from the interland. Furthermore, even when the loading information is available, the ideal layout of export containers in the storage area of the yard is almost impossible to be achieved due to the random arrival of containers. A way to avoid rehandle during a loading operation, would be container shuffling in advance of loading in order to group the containers by destination and weight. However, this necessitates additional workload for the handling equipment of an enormous scale, because the whole set of containers to be loaded must be arranged, probably in other stacks, in order to orderly remove them from the stacks for the loading operation, without any unproductive rehandles. Notice that this task could be performed only when the handling equipment is idle. Otherwise it would conflict with the ongoing tasks of loading other ships. In addition, smooth shuffling may require a buffer stacking area, where containers to be loaded are moved orderly from the storage area, which accommodates incoming containers from shippers. However, such a buffer area seems hardly practical or realistic for land scarce container terminals.

There is another type of rehandle, *unloading-related rehandle*, which refers to moving containers onboard that are not destined for being discharged at a particular port, to reach others that are to be unloaded at that port. This is likely to occur when containers destined for a specific port are spread out over several ship holds, being associated with the ship routing and different types of containers on board. The unloading-related rehandle may occur when limited ship capacity or strict stability condition in a complex itinerary of calling port requires containers with different destinations to be stowed mixed in a particular vertical column.

This paper is concerned with stowage and associated load planning of a containership while satisfying the ship's stability such as GM (the distance between the center of gravity and the metacenter position), list and trim, while minimizing the number of container rehandles. We focus only on the loading-related rehandle; therefore this problem may be restrictive in practical use. However, it is applicable in some cases for the following reasons: Our survey found that for several deep-sea shipping lines of Japan, each hold of a ship or a vertical column in a hold normally stows containers that are all destined for a particular port because the ship has few ports of call, resulting in fewer occurrences of the unloading-related rehandle. This is very likely especially when the ship is over-capacitated. In addition, even though a voyage calls at a number of ports, only a limited number of rehandles likely occur if the voyage itinerary forms the pendulum-type routing (a number of deep-sea routes are the pendulum) such as an itinerary of calling port: A-B-C-D-E-D-C-B-A. In deep-sea routes connecting two regions such as Asia-Europe and Asia-North America, little intra-regional traffic is observed. For instance, assume that ports A, B and C are situated in Japan and Korea while D and E are located in US. Deep-sea vessels move very few containers among A, B and C, and no traffic between D and E because of "cabotage". With such a trade pattern, containers for the farthest destination port of US in the calling sequence should be loaded, at each origin port in Asia, under those for the nearest destination port of US; and then, in the return voyage the same stowage arrangement can be applied because each port is called twice. This scheme results in quite few or even no unloading-related rehandles.

The ship's loading sequence associated with the stowage problem may affect a ship's handling time, since an inefficient loading sequence forces the handling equipment, especially the transtainer, to make redundant travels (or moves). Consequently, the stowage problem might include the loading sequence as another objective by taking into account the travel cost of the handling equipment. However, the container rehandle and the redundant travel of handling equipment should be measured by the time spent for those physical movements, as this is far more important. This study takes into account the rehandle as an obstructive factor to fast ship handling without quantifying it, as it is not easy to measure the time associated with those movements, which is beyond the scope of this study.

This paper is organized as follows. The next section reviews the related literature. In the third section the proposed algorithm is described. In the subsequent section, a variety of numerical experiments are carried out and presented, and the final section reports the paper's findings and conclusions.

2. Literature review

Stowage planning is a category of the loading problem, which is well recognized in the literature and has become widely used in a variety of transportation operations. Most of the work has been done for the Bin Packing Problem. Some of the studies formulate the problem as a 0–1 Mixed Integer Programming. They include the consideration of multiple carton sizes, and carton orientations. Other papers propose computer-based heuristics. An important consideration for loading is balance. Martin-Vega (1985) and Amiouny et al. (1992) developed a heuristic motivated by the problem of loading aircrafts or trucks: pack blocks into a bin so that the center of gravity is as close as possible to a target point. Mathur (1998) presented an efficient algorithm for a one-dimensional loading problem. The goal is to pack homogeneous blocks of given length and weight in a container in such a way that the center of gravity of the packed blocks is as close to a desired point as pos-

sible. The algorithm they proposed is based on the approximation of this problem as a Knapsack Problem, which is the problem of fitting into a sack of predefined maximum weight, items of different weights and different utilities so as to maximize the total utility of the sack. The loading problem associated with aircraft basically raises no rehandle issues due to its storage space characteristics.

The containership stowage and load-planning problem this paper addresses refers to the arrangement of containers inside the ship. This is much more difficult to solve than the aircraft and truck loading problems due to the fact that the ship's stowage plan has to consider the assignment of containers to a three-dimensional storage space in addition to the restrictions imposed in retrieving containers from the stacks in the field.

Although this problem is of high importance to the practitioners, few studies have been conducted on the container stowage and load planning. One of the early works on this problem was the one conducted by Imai and Miki (1989) who considered the maximization of *GM* and the minimization of the loading-related rehandle when loading containers onto one of the ship holds. For simplicity in the solution process, they formulated the problem as a two-objective assignment problem, employing the estimated number of rehandles in the objective function instead of the exact one. The precise number of rehandles is obtained from the resulting solution. Imai et al. (2001) followed another approach in order for the exact number of rehandles to be taken into account in the problem. They formulated the stowage problem as a *GM* objective assignment problem for identifying a noninferior solution set in terms of the *GM* and number of rehandles. Multiple solutions of the assignment problem were enumerated, thus computing the exact number of rehandles based on each enumerated solution. This approach, however, generated enormous multiple solutions for nearly the same range of a noninferior solution set as the method employed in Imai and Miki (1989). Surprisingly, the former took 6000 times longer computation time than the latter. Imai et al. (2002) modified the problem only for finding non-inferior solutions with acceptable *GM*.

Avriel and Penn (1993) and Avriel et al. (1998) addressed a stowage problem that only minimized the unloading-related rehandles without any consideration for ship's stability. They formulated the problem as a 0–1 Integer Programming and applied it for loading onto a single hold like Imai and Miki (1989). Furthermore, Avriel et al. (2000) developed some characteristics in the relationship between stowage planning and the coloring of circle graphs. Dubrovsky et al. (2002) implemented a GA-based heuristic for the same stowage-planning problem. Todd and Sen (1997) implemented a GA procedure with multiple criteria such as proximity in terms of container location on board and the minimization of unloading-related rehandle, transverse moment and vertical moment. Their study is interesting because it examined the relationship between the rehandle and the ship stability like the scope of this study; however their stability is not well defined as used in practice. Note that all the above studies do not assume that each vertical column in holds contains only containers of the same destination. Winter (1999) introduced the stowage planning in conjunction with load planning taking into account the equity of quay crane workload. This study also inspired issues of loading-related rehandle and ship stability; however it did not present any problem formulation with these criteria and the relevant solution method.

Martin et al. (1988) addressed the container ship load-planning problem for the transtainer system. Transtainer operation is a bottleneck in the loading process. A heuristic algorithm was developed, based on rules of thumb prevalent in the terminals. The objectives of the heuristic algorithm were the minimization of the transtainer movement time and the minimization of the number of unloading-related rehandles.

Haghani and Kaisar (2001) developed a heuristic algorithm for ship stowage planning with the minimization of the container handling cost (actually unloading-related rehandle), while keeping the ship's *GM* acceptable. They developed a heuristic for the problem. Although no other stability related factors were taken into account besides *GM* in the problem formulation, those factors such as trim and longitudinal moment were examined in

the heuristic. However, these factors were never explicitly evaluated in their solutions.

Wilson and Roach (1999, 2000) and Wilson et al. (2001) presented a realistic model, taking into account all technical restrictions in order to implement a commercial usable decision support system. Their approach was based on decomposing the planning process into two phases. In the first phase, called the strategic process, they created a rough stowage plan, based on grouping the containers with the same characteristics in terms of size, destination, etc., and on assigning them to blocks of stowage space in the ship. Ship stability was kept to an acceptable degree by this assignment process. These calculations were performed by a branch and bound procedure. In the second phase, called the tactical process, individual containers were assigned to specific locations, resulting in a detailed stowage plan. They employed a tabu search heuristic for the second phase calculation. Their objectives included, among others, the unloading-related rehandle and ship stability; however, no detail of the stability was described in their study. Due to the complexity of their solution methodology, they only show a solution result for a small sample problem; therefore its efficiency from the practical viewpoint is not shown.

More recently, Ambrosino and Sciomachen (2004) addressed a stowage-planning problem with the objective of minimizing the total stowage time where more practical constraints are taken into account such as different types of containers in length, weight limit being accepted for securing ship structure, etc. They assign some ship holds to containers with the same destination like this study in order to avoid unproductive work such as unloading-related rehandle. However, they do not explicitly take into account loading-related rehandle.

Kim et al. (2004) addressed a load-planning problem with an objective of proper arrangement of container stacks on board in light of smooth quay crane operation and the other of proper container retrieval sequence from container stacks in the yard in light of smooth transtainer operation. For this problem, they developed a beam search algorithm.

There have also been some other studies that are related to the containership load-planning problem. As mentioned previously, delay in container handling at a terminal depends mainly on the loading-related rehandle. Only Imai and Miki (1989) and Imai et al. (2002) address stowage planning, while taking into account the *GM*, for the reduction of the loading-related rehandle. Another approach for minimization of the delay is to arrange container storage location in yard stacks of arriving export containers so that unproductive rehandle is minimized for a given container ship stowage plan. Kim et al. (2000) proposed a dynamic programming model to determine the storage location so that the number of rehandles is minimized. The rehandle is also related to the storage space utilization on the yard. Taleb-Ibrahimi et al. (1993) tackled this issue by using an analytical model. Kim and Kim (1994) treated a similar issue but with a Mixed Integer Programming.

All in all, no research work has been conducted on the relationship between ship stability (i.e., *GM*, list, and trim) and the loading-related rehandle, which is the scope of this study. In this paper we do not take into account the unloading-related rehandle, since its consideration makes the problem considerably more difficult to solve while its practicality is diminished. In addition to that, this study is also motivated by the difficulty in determining a stowage plan in the context of the appearance of "mega" container ships. As described before, these ships call only at a very few selected hubs, making unlikely the probability of experiencing unloading-related rehandle, as the stowage spaces on board the ship are separated and dedicated to each specific port of call.

3. Problem definition and solution method

Whilst most major container terminals use either of the two handling systems: transtainer (Rail-Mounted Gantry Crane or Rubber-Tired Gantry Crane) and straddle carrier, the former has been getting more popular than the latter especially in major terminals with heavy traffic handled in a relatively small area such as those in Japan, because except for the case of the automated tran-

stainers used in Europe, the transtainer can handle containers stacked higher in the yard than the straddle carrier system. Therefore, throughout this section we consider the transtainer system for the model description, however it is easily adaptable to the straddle carrier system without any major change. In the transtainer system, storage space is portioned into multiple blocks, two of which are shown in Fig. 1.

The cellular (or LOLO) type container ship is considered in this study. Fig. 2 shows a typical cross-sectional view of a cellular ship. Each cell in the figure represents a slot where a container can be placed and the number in the cell implies the typical order of the loading process. Thus, the order of the loading process defines the vertical and horizontal locations (and longitudinal locations as well due to the multiple holds onboard) of containers being stowed in the ship hold. This principle combines the loading-sequence planning and the stowage planning. Usually the stowage
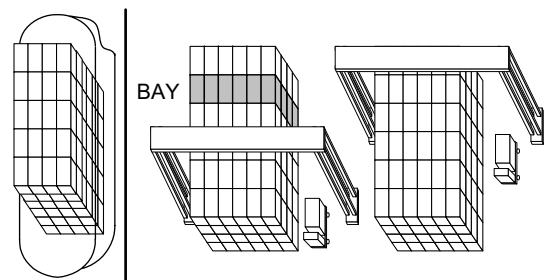

Fig. 1. Yard layout.

Fig. 2. Cross section of cellular container ship.

planning is separated from the loading-sequence planning. However, most Japanese shipping lines build a stowage plan in conjunction with loading sequence in order to reduce unproductive rehandle. Those shipping lines load containers onto a ship in a regular sequence like Fig. 2 because of possible human errors in loading tasks resulting from random loading. From the above discussion, the stowage planning combined with loading sequence seems a reasonable assumption, while in reality the loading sequence is planned a bit flexibly when a lot of rehandles are expected.

In this study, we assume that all containers are stowed in ship holds, but not on the upper deck. However, the model developed in this study is adaptable for the case with containers stowed both in holds and on the upper deck (or above hatch covers) without major modifications, if it is assumed that the containers above the hatch cover of a hold have the same destination port as the containers under the hatch cover. In addition, the model is applicable, without modifications, to the hatch-cover-less ships with containers above the upper deck. Note that it is also assumed that when a hold is not fully loaded, the containers are stowed with the top row being as flat as possible.

In the subsequent subsections, the stability related evaluation factors are described. We assume that each container has the same center of gravity, i.e. the weight is imposed at the center of the container along the three axes, even though the center of gravity of a particular container depends on its overall weight and mass distribution. However, the

assumption made is considered valid as most containers are full of small packages containing general merchandise and have their overall center of gravity at their middle location.

3.1. Stability-related factors

Ship stability is evaluated by three factors: GM, list and trim (see Derrett (1999) for details). Stability issues raised by list and trim are tractable by using the ship's ballast tanks, although they are normally adjusted within an acceptable range without using the ballast since the ballast is reserved for emergent incidents such as unexpected over-heavy cargoes to be loaded in the subsequent calling ports.

Among others the most important factor is the GM (more precisely the GM of the ship with loaded cargoes), which is the distance between the center of gravity (G) and the metacenter (M) as shown in Fig. 3(i) and calculated by the following equation.

$$GM = G_0M + \frac{\sum_i w_i \cdot lh_i}{\Delta_T} \qquad (1)$$

where lh_i is the vertical distance between the centers of gravity of the ship and container i, w_i is the weight of container i, Δ_S is the ship's displacement without cargo, Δ_T is the ship's displacement after containers are loaded $(\Delta_T = \Delta_S + \sum_i w_i)$ and G_0M is the distance between the center of gravity of the ship (G_0) and the metacenter (M).

The list, as shown in Fig. 3(i), caused by containers being loaded onto the ship is measured
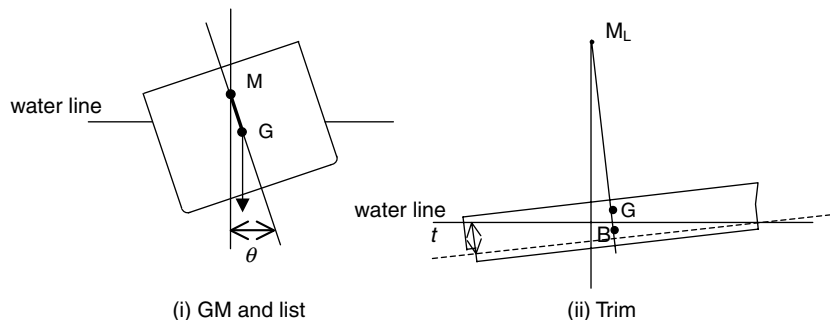

Fig. 3. Stability factors.

by $\tan \theta$ that is calculated by the following equation.

$$\tan \theta = \frac{\sum_i w_i \cdot lw_i}{\Delta_T \cdot GM} \qquad (2)$$

where lw_i is the horizontal distance between the vertical center of the ship and the center of gravity of container i.

As shown in Fig. 3(ii), the trim (defined as the total of change of drafts forward and aft) is given by Eq. (3)

$$t = \frac{L \sum_i w_i \cdot ll_i}{\Delta_T \cdot GM_L} \qquad (3)$$

where ll_i is horizontal length between the center of floatation and the center of gravity of container i, L is ship's length and GM_L is the distance between the center of gravity (G) and the longitudinal metacenter (M_L).

According to the Fig. 3(ii), the metacenter is located very high when the trim occurs; therefore, practically $GM_L \fallingdotseq BM_L$ is assumed, where BM_L defined by Eq. (4) is the distance between the center of buoyancy (B) and M_L.

$$BM_L = \frac{W \cdot L^3}{12 \Delta_T} \qquad (4)$$

where W is the ship's width.

Assuming the ship is a box, the trim is expressed by Eq. (5), which is obtained by inserting Eq. (4) into (3).

$$t = \frac{\sum_i 12 w_i \cdot ll_i}{W \cdot L^2}. \qquad (5)$$

3.2. Stability estimation

Based on the above definition of ship's stability factors, we formulate the stability related parameters being used in objective functions for the stowage problem.

As the GM is given by Eq. (1), the value defined by Eq. (6) is added to the G_0M when a container at position i of container stacks on the yard is loaded (in other words, that container is retrieved from position i of the stacks) as the jth container in the whole loading sequence, which is stowed in corresponding position of j of a ship hold (or a ship bay) as defined in Fig. 2.

$$\frac{w_i \cdot lh_j}{\Delta_s + w_i}. \qquad (6)$$

As the loading sequence numbers correspond to positions of containers onboard the ship, only $w_i \cdot lh_j$ depends on the container location onboard. We define this varying value in the GM by

$$G_{ij} = w_i \cdot lh_j. \qquad (7)$$

By using this definition we may formulate the problem only with the maximization of the GM as follows:

[PG]

$$\text{Maximize} \quad \sum_{i=1}^{N} \sum_{j=1}^{N} G_{ij} x_{ij} \qquad (8)$$

subject to

$$\sum_{j=1}^{N} x_{ij} = 1 \quad \forall \, i, \qquad (9)$$

$$\sum_{i=1}^{N} x_{ij} = 1 \quad \forall \, j, \qquad (10)$$

$$x_{ij} = \{0, 1\} \quad \forall \, i, j, \qquad (11)$$

where $x_{ij} = 1$ if a container at position i of container stacks on the yard is loaded in position j of ship hold as the jth container in the loading sequence; $= 0$, otherwise and N is the number of containers to be loaded.

In the formulation, constraints (9) and (10) ensure that every container is loaded with any order of loading sequence.

As seen in Eq. (2), the list definition includes the GM. The minimization of the list requires the maximization of the GM, that is another objective in the stowage planning. This enables us to only minimize $\sum_i w_i \cdot lw_i$ for the list objective. The following value (hereafter called *list contribution*) is added to the list objective when a container at position i is loaded as the jth container:

$$H_{ij} = w_i \cdot lw_j. \qquad (12)$$

Note that the list value is either negative or positive. The exact list objective is the minimization of the absolute value of the list. Assuming $GM > 0$, we may formulate the problem only with the minimization of the list as follows:

[PH]

$$\text{Minimize} \quad \left| \sum_{i=1}^{N} \sum_{j=1}^{N} H_{ij} x_{ij} \right| \tag{13}$$

subject to   (9)–(11).

In order to make this formulation solvable as a mathematical programming, we introduce Eqs. (15) and (16), resulting in the formulation [PH′].

[PH′]

$$\text{Minimize} \quad h^+ + h^- \tag{14}$$

subject to   (9)–(11),

$$\sum_{i=1}^{N} \sum_{j=1}^{N} H_{ij} x_{ij} = h^+ - h^-, \tag{15}$$

$$h^+ \geqslant 0, \quad h^- \geqslant 0. \tag{16}$$

In accordance with the trim definition (5), the value, $w_i \cdot ll_j$, is added to the trim objective when a container at position i is loaded as the jth container. Defining *trim contribution* as

$$T_{ij} = w_i \cdot ll_j \tag{17}$$

like the list, we may, therefore, formulate the problem only with the minimization of the trim as follows:

[PT]

$$\text{Minimize} \quad \left| \sum_{i=1}^{N} \sum_{j=1}^{N} T_{ij} x_{ij} \right| \tag{18}$$

subject to   (9)–(11).

Like the list, the trim formulation can be rewritten as follows:

[PT′]

$$\text{Minimize} \quad t^+ + t^- \tag{19}$$

subject to   (9)–(11),

$$\sum_{i=1}^{N} \sum_{j=1}^{N} T_{ij} x_{ij} = t^+ - t^-, \tag{20}$$

$$t^+ \geqslant 0, \quad t^- \geqslant 0. \tag{21}$$

3.3. Container rehandle estimation

Like Imai and Miki (1989) and Imai et al. (2002), we utilize the estimated number of rehan-dles in order to take the rehandle objective into account in the formulation. As described in the relevant literature for container rehandle (de Cas-tilho and Daganzo, 1993; Kim, 1994, 1997), the difficulty in estimating the number of container rehandles is caused by the random retrieve. This is typical for import container distribution; how-ever, it is also the case for export container loading. When loading containers, obviously the loading sequence is predetermined and this implies that container retrieve is programmed and not random. Consequently the number of rehandles can be calculated exactly. However, the exact calculation is based on a predetermined loading sequence available. Because of such a problem nature, it is quite difficult or even impossible to formulate the problem as a mathematical programming model, with evaluation of the exact number of rehandles. We alternatively introduce the idea of probability, in other words, the estimated number of rehandles to be examined, so that we formulate the problem as a mathematical programming model.

In Imai and Miki (2002), the rehandle is esti-mated based on the expected number of rehandles when retrieving each container in the block as the first one to be taken. With an assumption that con-tainer locations in a row of the yard are given the serial number, we let S_{ij} be the expected number of rehandles to withdraw a container of location i as the jth container. When withdrawing a target con-tainer (black box) in Fig. 4, we obtain the expected number of the hatched containers to be rehandled. Letting N be the number of containers in the row, a set of $j-1$ containers is retrieved with the proba-bility of $\frac{j-1}{N-1}$ before another container is loaded as the jth one. Thus, the probability that at least one of the $j-1$ containers is not retrieved, is

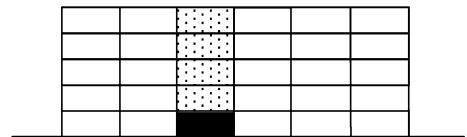$$1 - \frac{j-1}{N-1}. \tag{22}$$

Fig. 4. Container stack in a yard.

Therefore, the expected number of containers remaining above the jth retrieved container (i.e., hatched container in Fig. 4) before retrieval of the jth container, could be defined as the multiplication of the probability of Eq. (22) and the number of containers above the jth container (corresponding to a container of location i):

$$S_{ij} = \left(1 - \frac{j-1}{N-1}\right)B_i, \tag{23}$$

where B_i is the number of containers to be rehandled when a container at location i (black box in Fig. 4) is picked up as the first container in the loading sequence. Note that the figure of B_i is the one as of the state that the first retrieval takes place for the relevant container row. When we envisage container retrieval from the row, it is intuitionally recognized that a fewer number of rehandles is associated with a specific container retrieval if that container in the row is retrieved late (which means large value for j) because of the fact that blocking containers are more likely retrieved before that container. Also, when a container is the jth container to be retrieved, fewer rehandles are expected if fewer containers are initially piled as a row. These intuitions justify the Eq. (23). For instance, in Fig. 4 the estimated number is 3.86 if the black container is retrieved as the second (i.e., $j = 2$) with $N = 30$, while it is 3.45 if the black container is retrieved with $j = 5$. If the row has $N = 15$ containers with the same height as before, the estimated number associated with $j = 2$ is 3.71.

S_{ij} is a fairly good estimation for the observed number of rehandles with given loading sequences in terms of the total number of rehandles over an entire loading operation, according to experiments in Imai et al. (2002). Whilst in their study, the number is overestimated by the regression model they developed, there is a strongly linear positive association between the estimated and observed numbers; therefore the estimated number is useful in the minimization problem. The optimal solution to the formulation with the estimated number of rehandles is not the optimal in terms of the observed (or exact) number of rehandles, however the resulting solution is considered a good approximate one because of the close association between

the estimated and exact numbers as mentioned above. Of course, the observed number for the obtained solution is computed based on the loading sequence provided by the solution.

We compute the observed number of rehandles associated with a resulting solution, assuming that rehandled containers are moved back to the original locations (actually lower locations because of target containers) after picking up the target containers. We do not explicitly consider the places where the rehandled containers are temporarily stored while the target containers are processed. In the transtainer system they are stored in empty locations in the same yard bay in practice, while in the straddle carrier system they are stored in empty locations in the same single row. If no space is available for rehandling (while it is not likely because some spare place is reserved in practice for smooth rehandling), adjacent yard bays are used in the transtainer system and another place is used (for instance, the next row or reserved space in the yard) in the straddle carrier system.

Unlike Imai et al. (2002), this study assumes multiple stack rows on the yard and multiple bays onboard being involved in the container loading sequence. However, the entire container block split over several rows on the yard can be arranged as a single long row, making Eq. (23) applicable to this study, while N needs to be redefined for the arranged single row.

The rehandle objective formulation, then, follows:

[PR]

Minimize $\quad \displaystyle\sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij} \cdot x_{ij} \tag{24}$

subject to $\quad$ (9)–(11),

where the objective is the minimization of the estimated number of rehandles.

3.4. Formulation

Although the desirable GM is in general one meter, other GM values are used when taking into account other ship condition related factors. Furthermore, loading planners and ship officers in

charge of cargo handling may soften the *GM* and other stability restrictions in order to reduce the number of required container rehandles that prevent the quick ship turnaround. Such a trade-off analysis requires the set of noninferior solutions for our problem with multiple objectives.

Among a number of techniques for generating a noninferior solution set, we employ the weighting method (Cohon, 1978). In this method we define the problem as a mathematical programming model with a single objective that incorporates multiple objectives.

Putting the four objectives into a single objective with weights, we obtain the following formulation:

[PA]

Minimize $Z = \alpha \sum_{i=1}^{N} \sum_{j=1}^{N} G_{ij} x_{ij} + \beta \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij} x_{ij}$
$$+ \chi(h^+ + h^-) + \delta(t^+ + t^-) \quad (25)$$

subject to (9)–(11), (15), (16), (20) and (21),

where α, β, χ and δ are weights for the *GM*, rehandle, list and trim, respectively. Note that α is set negative because of the maximization of the *GM*.

3.5. Formulation for unbalanced initial setting

The formulation of [PA] assumes a container-loading scheme with the ship being empty. This is the reality in shuttle transportation between two ports of call. However, in most cases a ship has an itinerary with calling at more than two ports, where some containers are already left in ship holds in advance of loading containers at a particular port. Such an initial situation may cause the ship to be inclined. For this, we extend [PA] to reformulate it as follows:

[PA′]
Minimize Z
subject to (9)—(11), (16) and (21),

$$y_{jk} N_k^L \leqslant \sum_{j=1}^{N} j x_{ij} \leqslant y_{jk} N_k^H \quad \forall\ i, k, \quad (26)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{N} H_{ij} x_{ij} + \text{SH} = h^+ - h^-, \quad (27)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{N} T_{ij} x_{ij} + \text{ST} = t^+ - t^-, \quad (28)$$

where SH is the cumulative value of list contribution of containers left onboard, ST is the cumulative value of trim contribution of containers left onboard, $y_{jk} = 1$ if location j of the ship hold belongs to vertical column k and $= 0$ otherwise, N_k^L is the lower bound of storage location range (or equivalent in loading sequence number) applied for vertical column k and N_k^H is the upper bound of storage location range (or equivalent in loading sequence number) applied for vertical column k.

Since some containers already exist in each vertical column, containers to be loaded at the port of concern are to be stored on the top of them. N_k^L and N_k^H define the range of location for stowage of them in each column. Consequently constraint set (26) assures that containers are stowed in the range. In constraint sets (27) and (28), *SH* and *ST* are the existing factors in list and trim before loading at the port of concern.

3.6. Solution procedure using the genetic algorithm

As there is no polynomially-bounded time algorithm being found for [PA] (and [PA′] as well), we develop a heuristic algorithm by using the genetic algorithm (GA). Note that while all the solutions identified by the weighting method are noninferior, the solutions in this study are not necessarily noninferior due to the estimated number of rehandle being evaluated; therefore the set of noninerior solutions are reconstructed by computing the observed number of rehandles from the resulting solutions.

As GAs are widely applied for plenty of practical problems of mathematical programming, which are difficult to solve in terms of polynomially-bounded computational time, we do not explain the GAs in detail. The stowage-planning problems are minimization problems; thus, the smaller the objective function value is, the higher the fitness value must be. Having considered some alternative fitness functions, we employed the sigmoid function as defined in (29) where $y(x)$ denotes the objective function value:

$$f(x) = 1/(1 + \exp(y(x)/20000)). \quad (29)$$

For diversity in fitness value between individuals, the sigmoid function should be applied with x

ranging −2.0 to 2.0. Consequently, taking into account the objective function values in the experiments that are described in the next section, the sigmoid function has been defined as above. The mutation rate was set to 0.4, based on our preliminary experiments.

We apply the tournamenting process, which Ahuja et al. (2000) proposed for a better solution. One can apply a GA many times starting with different populations and choose the best individual obtained among all the runs. In order to save substantial running time, as an alternative they take the final population of two different runs, keep best 50% of the individuals in the two runs, and apply the GA again with this mixed population as the initial population.

4. Numerical experiments

4.1. Prelimainary analysis

The solution procedures were coded in "C++" language on a Sun SPARC-64G workstation. Problems used in the experiments were generated randomly, but systematically.

We first tried to compare solutions by GAs with and without tournamenting. The GA with tourna-

Table 1
Solution profile for cases of loading 504 containers

Case	Solution				CPU time (s)
	GM (m)	Rehandle	Heel ($\tan\theta$)	Trim (m)	
1	1.32	20	0.00	0.00	8150
2	1.27	22	0.00	0.00	6033
3	1.28	16	0.00	0.00	6144
4	1.28	19	0.00	0.00	6083
5	1.29	18	0.00	0.00	5884

menting outperformed in solution quality as expected, whilst its computation time is 7 times longer than the time without tournamenting. We next examined the solution quality in detail for five selected cases of loading 504 containers onto a ship with the capacity of that quantity. Table 1 demonstrates typical solutions for the five cases and the total computation times for obtaining a noninferior solution set. The stowage plan demonstrates a balanced stowage in terms of weight distribution, as the solution for case 4 is shown in Fig. 5 where darker boxes represent heavier containers.

4.2. Primary analysis

We set 22 cases with different ship sizes, handling volumes, container stack arrangements, initial ship conditions, and ship hold arrangements
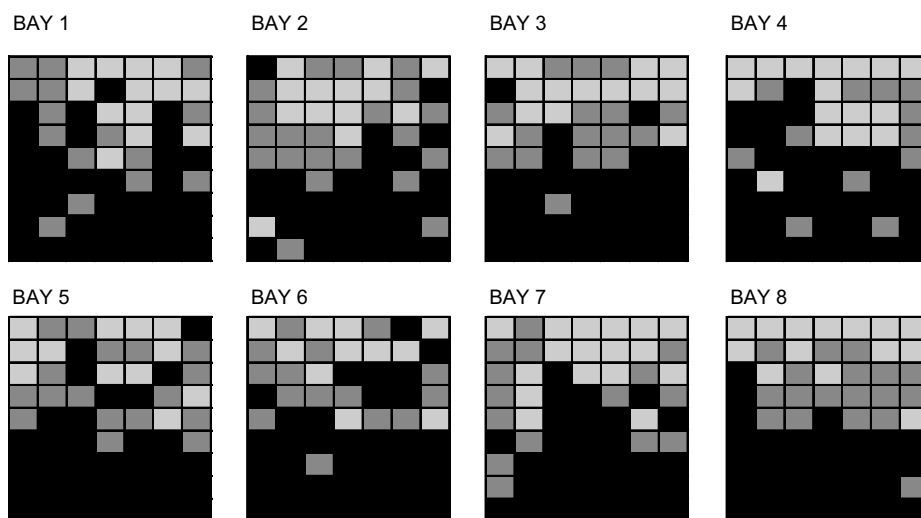

Fig. 5. Cross sectional view of containers on board.

Table 2
Computational cases

Case #	Ship size	Container volume	Stack arrang.	Initial ship cond.	Ship hold arrang.
1	S	M	R	L	R
2	S	M	W	L	R
3	S	M	R	L	D
4	S	M	W	L	D
5	S	M	D	L	D
6	S	F	R	H	R
7	S	F	R	T	R
8	L	M	R	L	R
9	L	M	W	L	R
10	L	M	R	H	R
11	L	M	W	H	R
12	L	M	R	T	R
13	L	M	W	T	R
14	L	M	R	L	D
15	L	M	W	L	D
16	L	M	D	L	D
17	L	M	R	H	D
18	L	M	W	H	D
19	L	M	D	H	D
20	L	M	R	T	D
21	L	M	W	T	D
22	L	M	D	T	D

Keys:
Ship size: S—capacity of 504 TEUs, L—capacity of 2016 TEUs.
Container volume: F—336 TEUs, M—504 TEUs.
Stack arrangement: R—random, W—grouped by weight, D—grouped by destination.
Initial ship condition: L—level, H—with list ($\theta = 10°$ and 15° starboard side for ship size = S and L, respectively), T—with trim (0.5 m by the stern for both ship sizes).
Ship hold arrangement: R—random, D—arranged by destination.

as shown in Table 2. When container stacks are grouped by weight (abbreviated by W), they are segregated into three weight levels. For the ship hold arrangement, "arranged by destination (D)" means that each hold is allocated solely to containers for a particular destination. In the small ship cases, four different destinations are assumed, each allocated to two ship holds; whilst in large ship cases three destinations are considered, each allocated to one hold, where the total of three holds are taken among others for loading. For each case, we prepare five different container stack arrangements (abbreviated as SA in subsequent figures for the results of the experiments) with uniform random numbers.

The sets of varied weight being employed for the experiments are shown in Table 3. The policy for setting these weights follows: weights for *GM*

(e) and rehandle (f) vary by 20, while holding $e + f = 100$. Given a set of e and f, weights for the list (g) and trim (h) range from 0 to 30 by 15. In accordance with the preliminary experiments, it is found that these weight sets produced so small amount of diversity for the list and trim that all four weights were adjusted as follows for the resulting weights α, β, χ and δ:

$$\alpha = -e \times 0.001,$$
$$\beta = f \times 0.700,$$
$$\chi = g \times 0.001,$$
$$\delta = h \times 0.004.$$

4.2.1. Small ship cases

We first examine cases 1 and 2, i.e. cases with random ship hold arrangement. Fig. 6 illustrates

Table 3
Weight sets

#	e	f	g	h
1	100	0	0	0
2	80	20	0	0
3	60	40	0	0
4	40	60	0	0
5	20	80	0	0
6	0	100	0	0
7	100	0	0	15
8	80	20	0	15
9	60	40	0	15
10	40	60	0	15
11	20	80	0	15
12	0	100	0	15
13	100	0	0	30
14	80	20	0	30
15	60	40	0	30
16	40	60	0	30
17	20	80	0	30
18	0	100	0	30
19	100	0	15	0
.				
.	same as sets 2 to 17 but with $g = 15$			
.				
.				
36	0	100	15	30
37	100	0	30	15
.	same as sets 8 to 17 but with $g = 30$			
.				
.				
48	0	100	30	30

the set of noninferior solutions for case 1. Due to difficulty in representation of the noninferior set, four evaluated objective values associated with each solution are plotted in increasing order of solution numbers that are given with increasing *GM* value (in meters). The rehandle value here is the observed one being calculated based on a resulting solution. The list (in $\tan\theta$) and trim (in meters) are given as absolute values in this and subsequent figures. The *GM* is inversely proportional to the rehandle, while the list and trim are confined to null but with little diversity for the trim. Although very small *GM* value is yielded for solutions 1–9, most solutions seem reasonable, having *GM* confined to the range of 1.0–1.4 m. This is also the trend for the experiment of case 2.

For cases 3 and 4 where ship holds are separately used for dedicated destinations, the overall trend is the same as for cases 1 and 2 but with many more rehandles. Such an increase in rehandle is caused by the ship hold arrangement for these cases. In contrast, containers can be likely stowed in any hold for the cases 1 and 2 with random hold arrangement, resulting in much fewer rehandles. For case 5 where separated container stacks on the yard are dedicated for specific destinations, fewer rehandles are observed compared to cases 3 and 4, because a group of containers at a particular stack are moved as a whole to its dedicated ship hold.

In the cases that some containers have already been stowed aboard the ship before loading and the ship leans as a result (cases 6 and 7), the overall trends for solution are the same as case 1.

4.2.2. Large ship cases

For cases 8–13 with the random ship hold arrangement, those results have overall the same trend as case 1. When the ship is initially inclined (cases 10 and 11), the resulting solutions have considerable diversity in the list as shown in Fig. 7 for case 10. Solutions when the ship's trim is by the stern, are almost the same as those with level and inclined conditions.

Next we examine the cases with the ship hold being arranged by destination (cases 14–22). The same trend exists for every set of cases regardless of the initial ship condition. With any ship condition, a typical observation for all the cases, except for the one with the yard stack arrangement by destination, is the enormous number of rehandles, as shown in Fig. 8 for case 14. This is caused by a strict restriction to the order of retrieving containers in the stacks due to the ship hold arrangement. In contrast, the case with the yard stack arrangement by destination (case 16) yields hardly any rehandle. In this case, a set of containers for a specific destination is intensively located in a particular stack and virtually retrieved by the lump to a particular ship hold. For all these cases, the list is nearly null and the trim is not null unlike other cases for large ships. The trend of the list and trim may be explained for the same reason.
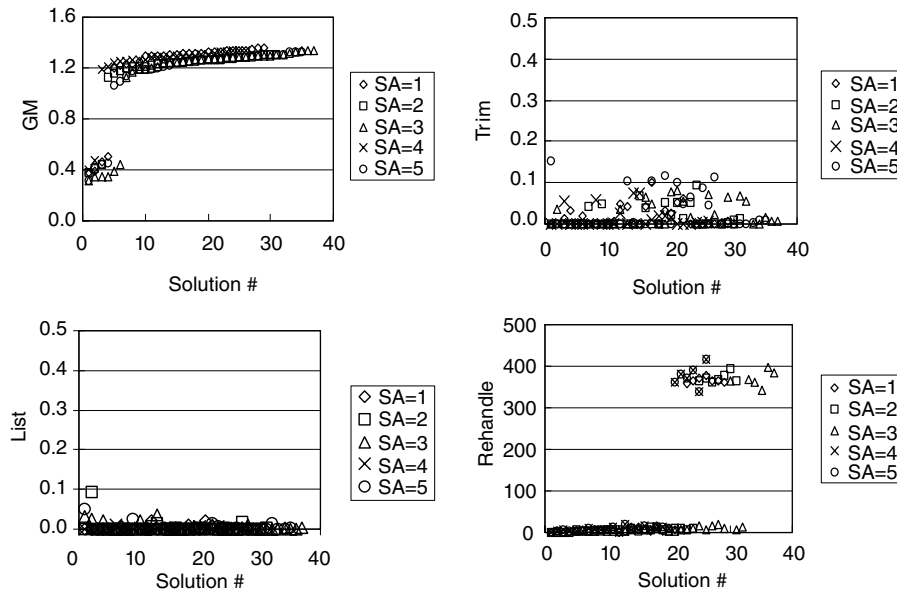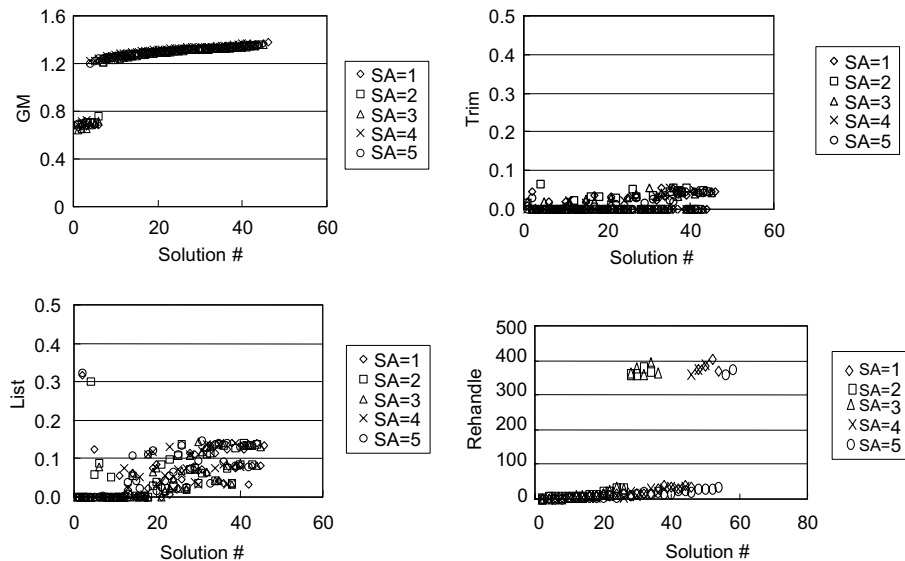
Fig. 6. Noninferior solution sets for case 1.

Fig. 7. Noninferior solution sets for case 10.

4.2.3. Solution improvement by reassignment of the order of the loading sequence

As described previously, a number of rehandles were observed when ship holds were arranged by destination. This is because all experiments as-

sumed only one quay crane being employed for the loading tasks of a specific ship. Normally big ships get two or three cranes assigned to them that work simultaneously for speedy loading/unloading, resulting in fewer rehandles. For such a
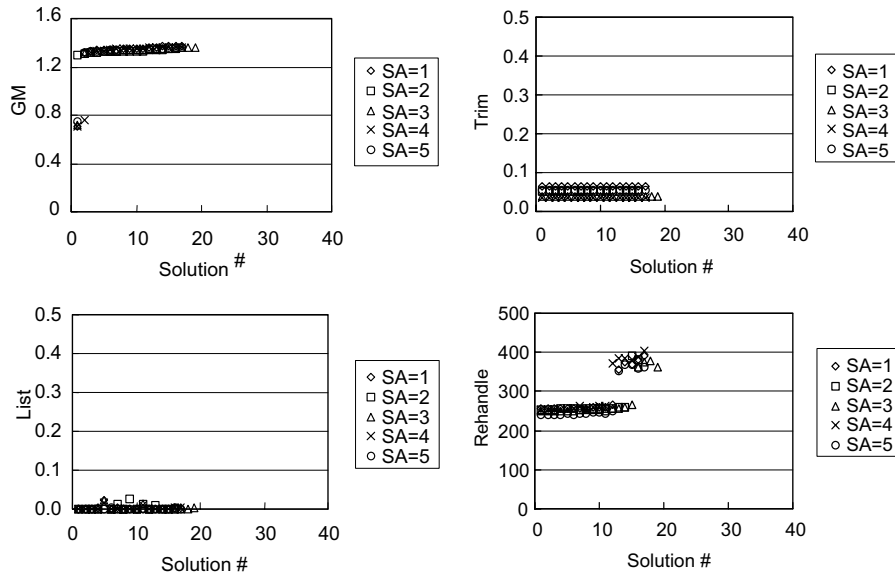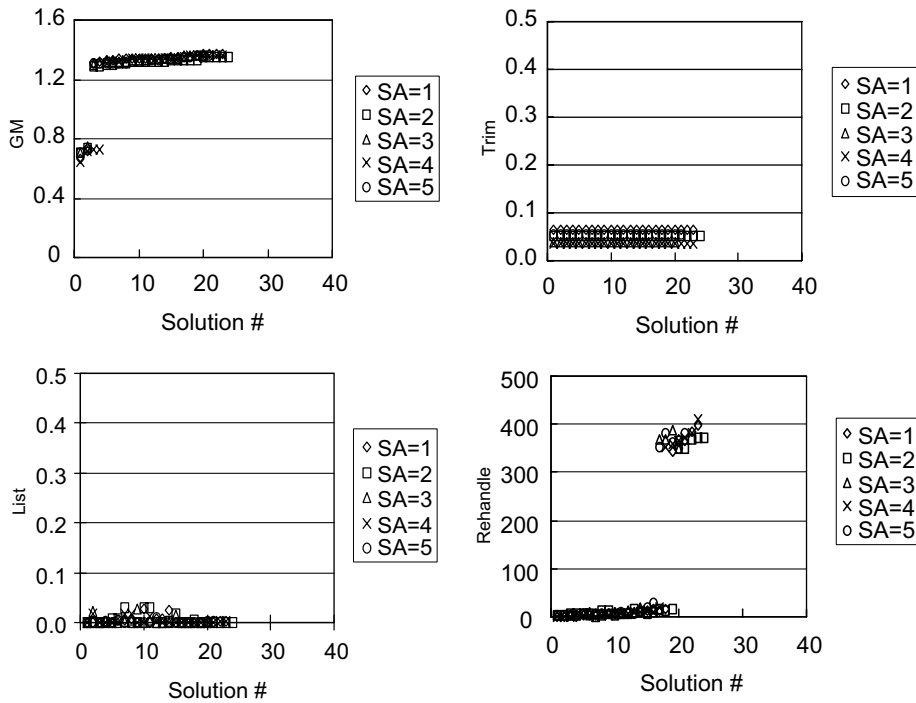
Fig. 8. Noninferior solution sets for case 14.

Fig. 9. Improved noninferior solution sets for case 14.

multi-crane loading, the same set of order of the loading sequence must be given for each subset of

containers handled by a particular quay crane; however this premise does not lead the formulations

[PA] and [PA′]. In order to facilitate the formulation, we assigned the order of the loading sequence to container locations from the first bay to the last bay onboard. While other strategies in assigning the order to the location onboard can be thought of, they do not affect the resulting solutions in terms of ship stability, i.e., the *GM*, list and trim, because they are computed based not on the sequence order but on the location onboard. This insight encourages us to apply a different assignment scheme of the sequence order to the location. We assume that multiple cranes engage loading tasks of multiple holds. Due to the unique sequence order to a specific location, we also assume that one crane handles its first container earlier than another crane handles its first container. Based on this premise, we may arrange the sequence order such that the first container (or the location onboard being treated first) handled by crane 1 corresponds to the first one, the first by crane 2 is the second one, the second by crane 1 is the third, the second by crane 2 is the fourth, etc.

By these recalculations, hardly any rehandle is observed even for those cases that yielded a lot of rehandles in the previous experiments. One such example is shown in Fig. 9 for case 14.

5. Concluding remarks

This paper addressed the problem of obtaining a noninferior solution set for the container ship stowage planning. For the ship loading tasks, a major concern is ship stability, typically the *GM*, list and trim. Another concern is container rehandling which occurs when specific containers are picked up from the container stacks on the yard. The problem was defined as a multi-objective integer programming, for which we obtained a set of noninferior solutions by using the weighting method. A wide variety of experiments demonstrated that the solutions by this formulation were acceptable for practical use when no rehandle takes place in unloading process. While we applied the GA with the tournament for better solution, its computation time is larger than one without the tournament. If terminal operators require faster

planning when our approach is implemented, they may use the algorithm without the tournament.

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