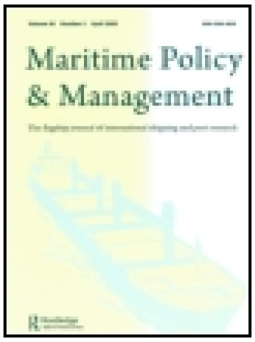

Maritime Policy & Management

The flagship journal of international shipping and port research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tmpm20

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To cite this article: Minsu Kim , Yoonjea Jeong & Ilkyeong Moon (2020): Efficient stowage plan with loading and unloading operations for shipping liners using foldable containers and shift cost-sharing, Maritime Policy & Management, DOI: 10.1080/03088839.2020.1821109

To link to this article: https://doi.org/10.1080/03088839.2020.1821109

Published online: 13 Sep 2020.

MARITIME POLICY & MANAGEMENT
https://doi.org/10.1080/03088839.2020.1821109

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Efficient stowage plan with loading and unloading operations for shipping liners using foldable containers and shift cost-sharing

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ABSTRACT

In this paper, we investigate the foldable container slot planning problem with loading and unloading operations that include shifting containers in a shipping line. We use the global optimal perspective in which a terminal operator generates an optimal stowage plan created on the basis of demand at subsequent ports. State-of-the-art foldable containers have been recently used in commercial maritime transport systems because they confer space-saving advantages when folded. We investigate container use through mixed-integer programming and shift cost-sharing methods as means to prevent conflicts between ports over inessential shifts and to provide guidelines for distributing shift costs among all ports in a logical and fair way. Through the proposed model, we found that most inessential shifts, considered inevitable from the local optimal perspective, can be eliminated, and the inevitable shift costs can be fairly distributed.

This article is a revised and expanded version of a paper entitled 'Shift Minimization with Loading and Unloading Operations using Foldable Containers' presented at the first Conference of the Yangtze-River Research and Innovation Belt(Y-RIB), Zhoushan, China; 2–5 December 2018.

KEYWORDS

operations research in maritime industry; container slot planning problem; foldable container; cost-sharing; shifting

1. Introduction

After McLean developed modern intermodal shipping containers in the middle of the 20th century, containerization has been widely employed in modern transport systems because it confers an economy of scale that leads to huge reductions in transportation and storage expenses. Moreover, goods inside a container can be delivered relatively undamaged and the containers can be transferred easily from one transportation mode to another. The advantages of containerization have a positive impact on the international trade conducted through containerships and other vessels.

To satisfy an increasing number of various customer demands, different types of containers are required and are typically classified according to their purpose of use. Every type of container follows the standard size as approved by the International Organization for Standardization (ISO): A *twenty-foot equivalent unit* (TEU) refers to 20-ft container that is 5.894 m long, 2.348 m wide, and 2.376 m high, but a *forty-foot equivalent unit* (FEU) refers to a 40-ft container that is 12.031 m long, 2.348 m wide, and 2.376 m high. These types of containers are called *standard containers*. Other types include reefer, open-top, flat rack, tank, bulk, pen, and ventilated containers.

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After the global financial crisis in 2008, container freight rates rapidly collapsed because of a severe economic recession in the international shipping industry. As a result, companies sought to minimize costs to operate their businesses in an efficient way. They strived to reduce unnecessary activities by improving unproductive operations, such as shifts in a port terminal. A *shifting (overstowage)* refers to the relocation of containers on a vessel through loading and unloading outbound and inbound containers to and from a vessel. For example, when an overstowed container, destined for a subsequent port, is stowed on top of an inbound container that must be unloaded at the current port of call, the overstowed container must be temporarily moved to another place and then reloaded onto the vessel; that is, it is shifted. Shifts are treated as a critical issue in coping with the efficiency of operation in a port and extensively studied in Avriel and Penn (1993). Chen, Lin, and Juang (2000) distinguished loading and unloading (discharge) operations by quay cranes into shifting and housekeeping, respectively. Both operations were linearly proportional to the volume of containers. Thus, this inefficiency has significantly expanded as the trade volume increases. Although all terminal operators do their best to remove the containers properly, shifts inevitably occur during the operations.

A stowage plan with shifts is unavoidably undertaken at each port because a preceding port does not consider the stowage plan for the next port; that is, a terminal operation in each port is implemented from a *local optimal perspective*. Moreover, each port can charge an additional shift cost to a preceding port because a precise cost-sharing plan related to shifts has not been established. Ambrosino, Sciomachen, and Tanfani (2004) and Ambrosino, Paolucci, and Sciomachen (2013) stated that ship coordinators are responsible for giving off the instructions of stowage plans with regard to container information such as bay availability, destinations, requirements for special containers. Every stowage plan in a regular route can be well known among ports due to the instructions of the ship coordinator. Nevertheless, research on the cooperation between ports is not extensively studied for considering the plan of a subsequent port when a preceding port lay outs the plan. Furthermore, when interviewing with industry practitioners from Pusan Newport Company, they were also not aware of the relevant study and raised up issues regarding the calculation of surcharge for unexpected shifts caused by a preceding port. Rather, they pointed out that this surcharge is payable based on a rule of thumb. Every destination of a shipping line is already determined and the variation of demand in each port can be negligible. Therefore, the cost can be properly forecasted after an entire stowage plan for the line is established.

Despite total international trade gradually expanding as a result of worldwide economic growth, on the basis of year-to-year recovery since 2008, the World Trade Organization reported that the trade imbalance between exports and imports in 2015 had grown because the eastern and western worlds are export- and import-oriented, respectively. For example, according to PIERS data in 2017, export volume from the United States to China is 2.8 million TEU whereas the volume from China to the United States is 13.5 million TEU. This imbalance has caused an increase in the repositioning of empty containers while full containers are transported on a vessel. Approximately 20% to 30% of loaded containers are empty. Hence, a terminal operator struggles to achieve efficiency due to the limited capacities of storage areas in the container yard and container slots on board. Instead of receiving new full containers, empty containers occupy storage areas, only decreasing the profits for shipping companies that own containers. Storage costs keep increasing when empty containers stay in port longer. Zhang and Facanha (2014) provided several strategies to deal with an inefficient storage such as dedicated fleet and rail terminal for economies of scale as well as utilizing U.S. ports along with the west coast for an easier access to Asia. In particular, foldable container, 4 ~ 6 folded containers in a stack equivalent to the size of a standard container, is another state-of-the-art strategy in practice. This container shows a great benefit in transportation and storage. In particular, Bandara et al. (2015) anticipated that the total number of empty containers used in the port of Melbourne would be reduced by 80% until 2035 after the widespread adoption of foldable containers in the shipping industry. Other ports in Australia would achieve similarly significant reductions in container usage. Therefore, foldable containers are required in the global market to solve the storage issues by reducing the volume of an empty container in a yard, or as addressed in this study, in a vessel.

In this study, we generated an efficient loading and unloading plan by considering foldable containers to minimize the total number of quay crane (QC) operations, including shifts, for a terminal operator. Using a global optimal perspective, we also developed two cost-sharing methods in an effort to eliminate the unnecessary shifts generated by a local optimal perspective and fairly distribute the shifting costs among the ports in a shipping line. The organization of this paper is as follows: A literature review on stowage plans and foldable containers is presented in Section 2, and Section 3 explains the problem, including descriptions of the vessel structure and overviews of the shipping line, shift cost, foldable container, and global optimal perspective. Mathematical models for the stowage and cost-sharing plans are presented in Section 4. Section 5 shows the computational experiments and analyses to provide useful insights and implications. The conclusion of the paper is presented in Section 6.

2. Literature review

In this section, we present literature essential to our study, based on two main topics: stowage plans and foldable containers. Delgado et al. (2012) developed an integer programming (IP) model for the slot planning problem to which our proposed mixed-integer programming (MIP) model mainly refers. In their model, all containers were loaded and distributed from the first port to the remaining ports while the numbers of overstows, different destinations for containers in a stack, stacks to be used, and reefer slots to be used were minimized. Because the slot planning problem is known to be NP-hard, Delgado et al. (2012) also presented a constraint programming model for fast optimal stowage at container vessel bays. Moura, Oliveira, and Pimentel (2013) proposed an optimization model for a container vessel with no fixed routes by considering demands and delivery deadlines that minimize the total routing cost and the number of shifts in short-sea shipping. Their MIP model contributed to the efficient management of small vessels for reducing transportation times and delivery costs.

Ambrosino, Paolucci, and Sciomachen (2013) extended the original optimization model of the master bay plan problem developed by Ambrosino, Sciomachen, and Tanfani (2004) to the multi-port. They incorporated two exact MIP models to minimize the numbers of unloaded and re-handled containers. Two different heuristic approaches were presented to solve large instances by both models. Also, Ambrosino et al. (2017) developed new fast MIP model to solve the real size of the problem. Kang and Kim (2002) also studied a stowage planning problem for arranging containers on a vessel that minimizes the time required for shifts and QC operations on a vessel tour by maintaining ship stability. They developed a heuristic approach in which the problem is decomposed into two sub-problems. The results from the problems were used in each iteration by applying greedy and tree search algorithms. Not only the number of QC operations is taken into account, but also its path for crane movement in container yard can be optimized. Chen (1999) investigated impacts on terminal operation in container yard and unproductive moves in the terminal. Dik and Kozan (2017) proposed algorithms based on tabu search to deal with the optimal path of crane movement and number of the operations. Some researchers solved a stowage planning problem through conventional solution approaches. Wei-Ying, Yan, and Zhuo-Shang (2005) decomposed the problem, referred to as the containership stowage problem, into two sub-problems and incorporated two objective functions to minimize the numbers of bays and overstows. A tabu search algorithm was proposed to solve the sub-problems. Although they realized that a stowage plan from a preceding port influences the plan at the current or subsequent port, the issue was not extensively addressed in their paper. Wilson and Roach (2000) and Pacino et al. (2011) also studied stowage planning model with multi ports.

The Pareto clustering search algorithm was proposed to solve the 3D containership loading plan problem to minimize the number of necessary loading and unloading operations and reduce the instability of the ship (Araujo et al. 2016). They also used a local search along with Pareto clustering search algorithm to lay out the options for a decision maker. To overcome the complexity of the binary IP model, Ding and Chou (2015) focused on providing a heuristic algorithm to minimize the number of shifts, which are considered the unproductive movement of containers. Shifts may be undertaken at each port, except the first and last, while loading and unloading outbound and inbound containers. Their heuristic algorithm outperformed the one developed by Avriel et al. (1998) through use of extensive computational experiments. Avriel, Penn, and Shpirer (2000) showed that if the number of columns of bays is more than three, the shift problem follows NP-completeness.

Not only efficiency of QC operations for a vessel can be increased by minimizing shifts, but also some literature strives to improve the efficiency of container yard (CY) by rearranging the positions of containers for QC operations. A reshuffling operation is necessary in CY when a container positioned below others must be unloaded (Lehnfeld and Knust 2014). Monaco, Sammarra, and Sorrentino (2014) studied the terminal-oriented ship stowage planning problem by developing the binary IP model to minimize transportation and reshuffling times. They also proposed a Tabu Search algorithm for obtaining sub-optimality for the problem. Zhang et al. (2015) conducted a similar study, but from the perspective of a terminal operator. They formulated the MIP model for a two-stage double-cycle operation to minimize operation times for quay and yard cranes at the QC and YC stages, respectively. For evaluating performances, they developed models and a bi-level genetic algorithm to be compared with a lower bound. Other approaches for a CY were employed by Lee, Kim, and Yun (2011), who evaluated the handling capacity of a yard crane in advance by estimating the expectations and variances through statistical analysis, and they showed the impact of interdependent handling times on the expectation and variance of the cycle time. Jeong et al. (2012) also conducted a simulation study to verify the effectiveness of a space-planning method and performance of a new QC scheduling method. Moreover, Lee and Mingzhu (2012) emphasized on the importance of utilizing container terminal yard and remote container yard because the storage capacity of CYs is extremely limited comparing to the inflow of containers toward port areas before the shipment. They therefore developed a storage-pricing model on the basis of game theory for the competition between container terminal yard and remote container yard.

Because a foldable container has a distinct advantage in reducing its size when folded, research on maritime topics, other than a stowage plan, has been conducted for an empty container repositioning problem. Moon and Hong (2016) introduced foldable containers in their mathematical model to reposition empty containers with minimizing total transportation, inventory holding, handling, folding and unfolding, leasing, and installing costs. Linear programming based and hybrid genetic algorithms have been used to obtain heuristic solutions within reasonable computation times. By using a sensitivity analysis, they then showed the effect of using a foldable container. Other researchers investigated similar issues; see, for example, Konings (2005), Moon, Do Ngoc, and Hur (2010), Moon, Do Ngoc, and Konings (2013), Satir and Basarici (2019), and Goh (2019). Shintani, Konings, and Imai (2010) revealed the cost effectiveness of a foldable container in an empty container repositioning problem in the hinterland.

Although the advantages of foldable containers have been extensively reported in the existing literature, Shintani, Konings, and Imai (2012) pointed out that a foldable container involves high development, handling, manufacturing, repair, and maintenance costs. Moreover, to realize significant cost savings in transportation by using foldable containers, some challenges, such as achieving economies of scale, must be properly addressed (Wang et al. 2017; Zhang, Zhao, and Moon 2018). In addition, because foldable containers have not yet been standardized, the companies developing them, including Holland Container Innovations and Korea Railroad Research Institute, face fierce competition from other manufacturers in the race to achieve standardization. Despite the challenges, significant savings are likely to be realized in the hinterland and maritime transportation, storage, and container handling operations by QC when these containers are widely commercialized in the future.

Table 1. Comparison of this study with stowage planning literature.

	Mathematical model	Problem characteristics	Perspective type	Rolling horizon	Coordination mechanism
Ambrosino et al. (2017)	MIP	Master bay planning with reefers and open-tops	L	-	-
Araujo et al. (2016)	-	3D container loading plan	L	-	-
Avriel et al. (1998)	BIP	Dynamic slot-assignment for shifts	G	-	-
Avriel, Penn, and Shpirer (2000)	-	The complexity of shift problem	G	-	-
Delgado et al. (2012)	IP	Slot planning with reefers	L	-	-
Ding and Chou (2015)	-	Shift minimization with heuristics	G	-	-
Kang and Kim (2002)	IP	Stowage planning with shift minimization	L	-	-
Moura, Oliveira, and Pimentel (2013)	MIP	Ship routing with stowage	L	-	-
This study	MIP	Stowage planning with foldable containers	G		Shift cost-sharing

'L' represents local optimum and 'G' represents global optimum
"-" represents none and '□' represents covered

Table 1 summarizes the relevant studies on stowage planning problems with different solution approaches. As can be seen from the table, most existing literature does not consider the global optimal perspective in an attempt to optimize entire system operations alongside providing rolling horizons and coordinated efforts. Moreover, foldable containers require special handling in circumstances of loading and unloading operations and are not extensively introduced in existing stowage planning literature.

3. Problem definition

The capacity of a vessel dramatically varies in the numbers of cells, stacks, and bays by vessel types. The number of cells is called a tier indicating the row of a stack. The overview of container slots on a vessel is shown in Figure 1. In this study, 20 ft and 40 ft standard containers and 40 ft foldable containers can be assigned to cells. Indeed, although another type of container such as 45 ft standard or reefer is also utilized in practice, only 40 ft foldable container is available up to the present. Thus, these three types would be considered in this paper for model simplification. Stack numbers are labeled in sequence from left to right, and tiers are numbered in sequence from top to bottom as shown in Figure 2.

Each stack has weight and height limitations for maintaining the stability of a vessel. This constraint is considered a critical issue in safety code for voyage because it might cause a severe shipwreck or containers to be collapsed from stacks. In particular, cross-equilibrium balance plays

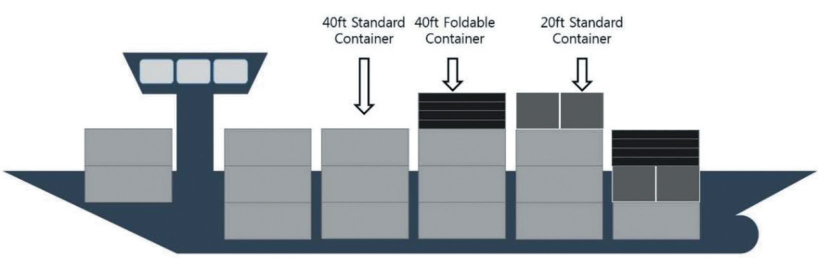

Figure 1. Arrangement of container slots on the vessel with 40 ft standard and foldable containers and 20 ft standard container.

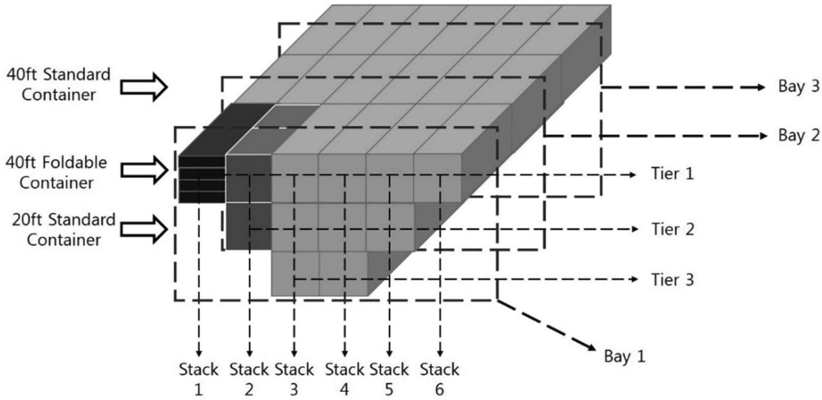

Figure 2. Stacks and tiers with 40 ft standard and foldable containers and 20 ft standard container in a bay.

a key role in preventing catastrophic accidents that may occur when a vessel is steered to the left or right. This constraint implies that the maximum tolerance for differences between left and right hatches cannot exceed the predetermined limit.

Foldable containers must be handled with greater care than standard containers. Because purchase cost of a foldable container is two or three times that of a standard container. When containers are transported on seaborne routes, approximately 20%—30% of the containers on a vessel are damaged by the pressure of other stowed containers, corrosion from salt water, and severe waves. Although special handling rules for foldable containers have not been established in practice, this study provides protection rules for preventing damage from other containers. Therefore, this paper proposes preventive rules to minimize possible damage in consideration of the impacts of pressure, salt water, and waves; that is, foldable containers should be always stowed on top of another type of container.

In general, a shipping line is composed of cyclic routes. Although potential loading and unloading operations occurring in the future cannot be fully considered, we can still achieve the global optimum for the entire supply chain by using a rolling horizon. Figure 3 illustrates the difference between global and local optimal perspectives in terms of the planning horizon. This figure specifically demonstrates how Port 1 and Port 2 consider the stowage plans of subsequent ports until Port 3 and Port 4 are reached, respectively, using a rolling horizon.

The ultimate goal of this study is to investigate unproductive moves of loading and unloading operations under technological constraints related to foldable containers and practical stacking rules for a shipping line to minimize shifts along with total costs. In this regard, the cost-sharing method for shifts is also developed with the expectation of resolving disputes over distributed costs among ports. Several assumptions of the problem are summarized as follows:

(1) All relevant container information is deterministic.

(2) All containers are loaded, unloaded, or shifted, or remain in their original positions in a vessel at each port.

(3) Two 20 ft standard containers are assigned as a pair in a cell.

(4) Cross-equilibrium balance is considered at each port.

(5) No standard containers can be stowed on the top of a bundle of empty folded containers.

(6) Foldable containers are in the folded form with abundle of the four containers to be loaded or unloaded on avessel and independent of QC operations.

(7) QCs are operated with single-cycle-twin-lift modality to load or unload a pair of 20 ft standard, a single 40 ft standard, a bundle of empty folded containers.

(8) The first and last ports are selected based on a rolling horizon.

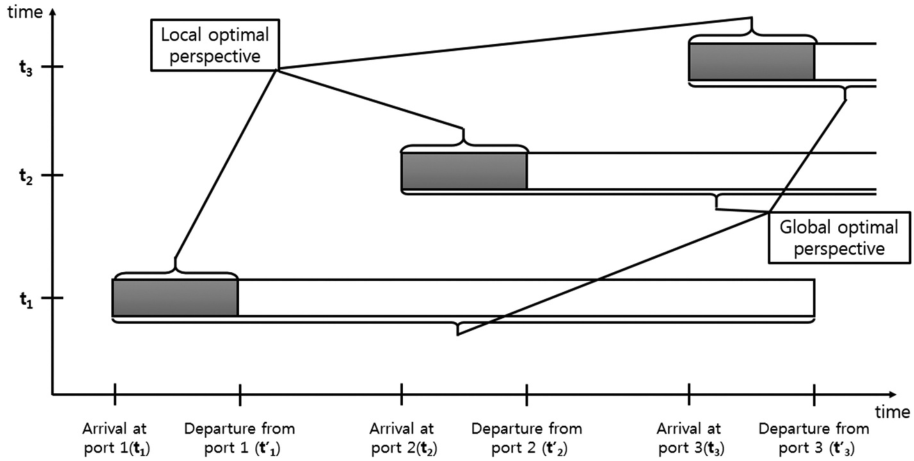

Figure 3. The planning horizon at each port from a local optimal perspective (gray area only) and global optimal perspective (gray and white areas).

With informal arrangements, a port operator can typically charge additional fees to an operator from the preceding port for unexpected QC operations. In addition, to the best of our knowledge, the surcharge is calculated based on a rule of thumb in practice, and no standard cost-sharing method for charging shifting costs has been presented in existing literature. Therefore, a specific and logical model for the sharing of shifting costs also should be developed, along with an articulation of the conditions under which many shifts are likely to occur.

In the next section, we developed a mixed-integer programming model that minimizes the total number of shifts from a global perspective, and we proposed two methods for sharing those shift costs.

4. Mathematical model

In this section, we propose the MIP model and two cost-sharing methods. For the MIP model, we adopted a notation similar to that of Delgado et al. (2012). However, in our model, objective function and constraints related to ship stability and a foldable container, differ from those they used.

4.1. Mixed-integer programming model

Notation for parameters, sets, and decision variables used to formulate the model for the container-slot-planning problem with foldable containers are listed in Table 2. The decision variable,c_p^{jkbi}, represents the current container location on a vessel at each port. Using n_p^{jkbi} and c_p^{jkbi}, we can detect any change in container placements in cells. n_p^{jkb} is used for observing any change in cells regardless of container types. The value of this decision variable is used to determine m_p^{jb} along with LC^{jb}. Thereafter, we can calculate the total number of QC operations, as shown in n_p^{CO}.

In addition, o^i shows the priority order of a stowage sequence for containers. The stowage sequence calls for a foldable container to always be stowed on top of a standard container to avoid severe damage from the weight of the standard one. The priority order could be generally applicable to other types of containers as well. Ports from the first to the last on the planning horizon are sequentially assigned numbers from 1 to p, and ports before and after this horizon are expressed as 0

Table 2. Parameters, sets, and decision variables in the MIP model.

Sets	
I	set of containers, indexed by i
T	set of 20 ft standard containers, $T \subset I$
F	set of 40 ft containers, $F \subset I$
J	set of stacks of vessel, indexed by j
B	set of bays of vessel, indexed by b
K	set of tiers of vessel, indexed by k
SC	set of cells in tier k and stack j belonging to bay b, indexed by (k,j,b)
P	set of port p
SCR	set of cells in tier k and right stack j belonging to bay b,$SCR \subset SC$
SCL	set of cells in tier k and left stack j belonging to bay b,$SCL \subset SC$
Parameters	
w^i	weight of container i
W^j	weight limit of stack j
o^i	priority order of stowing container i in a vessel
LC^{jb}	number of loadable cells in stack j belonging to bay b
$L_p^i \in \{0,1\}$	indicates whether container i is loaded at port p
$U_p^i \in \{0,1\}$	indicates whether container i is unloaded at port p
Q	maximum cross-equilibrium tolerance
Decision Variables	
c_p^{jkbi}	container i being stowed in tier k and stack j belonging to bay b at port p (binary variable)
n_p^{jkbi}	indicates whether container i is occupied in tier k and stack j belonging to bay b at port p as it was in the previous container position at port p (binary variable)
n_p^{jkb}	indicates whether container slot in tier k and stack j belonging to bay b carries the same container after loading operation at port p (binary variable)
n_p^{CO}	total number of QC operations at port p (integer variable)
m_p^{jb}	the lowest cell in stack j belonging to bay b where any type of containers are loaded, unloaded, or shifted at port p (integer variable)
α_p^{jkbi+}	intermediate variable for calculating n_p^{jkbi}, if container i is stowed in tier k and stack j belonging to bay b at port p and $p+1$, then 1; else 0 (binary variable)
α_p^{jkbi-}	intermediate variable for calculating n_p^{jkbi}, when container i is not stowed in tier k and stack j belonging to bay b at port p and $p+1$, then 1; else 0 (binary variable)

and $p+1$, respectively, to indicate dummy ports. More details on these notations are provided in Table 2.

The proposed mathematical model for reducing shift operations under structural, operational, technological constraints is developed as follows:

$$\min \sum_{p \in P} n_p^{CO} \tag{1}$$

$$\frac{1}{2}\sum_{i \in T} c_p^{jkbi} + \sum_{i \in F} c_p^{jkbi} \leq 1 \qquad p \in P, (k,j,b) \in SC \tag{2}$$

$$\sum_{(k,j,b) \in SC} c_p^{jkbi} = \sum_{q=0}^{p} \left(L_q^i - U_q^i\right) \qquad i \in I, p \in P \cup^{\{0\}} \tag{3}$$

$$\sum_{t \in T} c_p^{jkbt} \geq 2c_p^{jkbi} \qquad i \in T, p \in P, (k,j,b) \in SC \tag{4}$$

$$\sum_{k \in K} \sum_{i \in I} w^i c_p^{jkbi} \leq W^j \qquad p \in P, (k,j,b) \in SC \tag{5}$$

$$\frac{1}{2}\sum_{i \in T} o^i c_p^{j(k-1)bi} + \sum_{i \in F} o^i c_p^{j(k-1)bi} \leq \frac{1}{2}\sum_{i \in T} o^i c_p^{jkbi} + \sum_{i \in F} o^i c_p^{jkbi} \qquad p \in P,$$

$$(k,j,b) \in SC, k \neq 1 \tag{6}$$

$$-Q \leq \sum_{(k,j,b)\in SCR} \sum_{i\in I} w^i c_p^{jkbi} - \sum_{(k,j,b)\in SCL} \sum_{i\in I} w^i c_p^{jkbi} \leq Q \quad p \in P \tag{7}$$

$$c_{p-1}^{jkbi} + c_p^{jkbi} - 1 = \alpha_p^{jkbi+} - \alpha_p^{jkbi-} \quad i \in I, p \in P, (k,j,b) \in SC \tag{8}$$

$$\alpha_p^{jkbi+} + \alpha_p^{jkbi-} = 1 - n_p^{jkbi} \quad i \in I, p \in P, (k,j,b) \in SC \tag{9}$$

$$n_p^{jkb} \leq \sum_{i\in I} n_p^{jkbi} \leq 4n_p^{jkb} \quad p \in P, (k,j,b) \in SC \tag{10}$$

$$kn_p^{jkb} \leq m_p^{jb} \quad p \in P, (k,j,b) \in SC \tag{11}$$

$$m_p^{jb} \geq LC^{jb} - \sum_{k\in K} \left(\frac{1}{2} \sum_{i\in T} c_{p-1}^{jkbi} + \sum_{i\in F} c_{p-1}^{jkbi} \right) \quad p \in P, (k,j,b) \in SC \tag{12}$$

$$\begin{aligned} &2\sum_{b\in B}\sum_{j\in J}\left(m_p^{jb} - \left(LC^{jb} - \sum_{k\in K}\left(\frac{1}{2}\sum_{i\in T} c_{p-1}^{jkbi} + \sum_{i\in F} c_{p-1}^{jkbi} \right)\right)\right) \\ &+ \frac{1}{2} \sum_{i\in T}\left(L_p^i - U_p^i \right) + \sum_{i\in F}\left(L_p^i - U_p^i \right) = n_p^{CO} \quad p \in P, (k,j,b) \in SC \end{aligned} \tag{13}$$

$$c_p^{jkbi} \in \{0,1\} \quad i \in I, p \in P, (k,j,b) \in SC \tag{14}$$

$$n_p^{jkbi} \in \{0,1\} \quad i \in I, p \in P, (k,j,b) \in SC \tag{15}$$

$$n_p^{jkb} \in \{0,1\} \quad p \in P, (k,j,b) \in SC \tag{16}$$

$$n_p^{CO} \in Z_+ \quad p \in P \tag{17}$$

$$m_p^{jb} \in Z_+ \quad j \in J, b \in B, p \in P \tag{18}$$

$$\alpha_p^{jkbi+}, \alpha_p^{jkbi-} \in \{0,1\} \quad i \in I, p \in P, (k,j,b) \in SC \tag{19}$$

The objective function (1) minimizes the total number of QC operations, including loading, unloading, and shifting activities, for an entire shipping line within one cycle (defined as starting at the first port and ending at the last port on the line). Constraint (2) ensures that at most either a pair of 20 ft or single 40 ft containers is stowed in a cell. Constraint (3) requires any type of container being stowed in exactly one cell until unloaded at the determined destinations. It also shows the current container located in a cell at each port, illustrating that the location is updated whenever a shift occurs during loading and unloading operations. In addition, we used a dummy variable, c_0^{jkbi}, to realize real operational conditions in a shipping line; that is, it is assumed that a vessel carries loaded containers in certain container slots when it arrives at the first port. The number of 20 ft standard containers that must be in a pair is presented in Constraint (4). Constraint

(5) represents the weight limits of stacks necessary for maintaining the stability of a vessel. Constraint (6) indicates that the type of container must be strictly allocated on top of other containers. The stability of a vessel attributable to cross-equilibrium is shown in Constraint (7). Constraints (8) and (9) count the number of QC operations. This counting procedure is initiated whenever containers are loaded, unloaded, or shifted. Constraint (10) ensures that any type of container is counted as 1 regardless of the number of operations at each port. For each cell, $4n_p^{jkb}$ shows that 4 is the maximum number of loading and unloading operations because every 20 ft standard container must be paired with another for any operation in this model. Constraint (11) locates the lowest cell in a stack in which any container is loaded, unloaded, or shifted at a port. Constraints (11), (12), and (13) are designed to count the total number of QC operations by identifying any movement for inbound and outbound containers in cells. Constraints from (14) to (19) define decision variables.

Avriel, Penn, and Shpirer (2000) proved that the minimum-shift problem is NP-complete, and their problem can be reduced to our problem. In particular, their shift problem considers a transportation matrix, expressed by the number of standard containers transported from ports i to j, so that their input data should be properly converted to our problem instance. To do that, however, one needs to establish container indices and container weights as zero, in order to apply the data of their shift problem to our problem. In this way, an optimal solution to their problem could be obtained by finding an optimal solution to our problem. Their shift problem could be considered the special case of our problem so that our problem also follows NP-completeness. In addition, because the number of decision variables is proportional to the number of cells, ports, and containers, computation times increase exponentially along with large problem instances.

4.2. Cost-sharing

After establishing the stowage planning through our model, each port should be imposed by fairly distributed shift costs. Calculating shift costs accurately at each port is challenging because of the difficulty in identifying an exact cause for a shift. In other words, the port responsible for a shift remains unclear. For instance, outbound and inbound containers are handled in origin and destination ports such that both ports seem accountable for shifts. However, the terminal operator at the latter ports may believe that the preceding port failed to generate a stowage plan that accounts for the operations of subsequent ports. To resolve the ambiguity over shift responsibility we propose two practical methods for a reasonable cost-sharing for shifts.

The first method is considered as *a freight volume proportional method*. Because the entire journey of a shipping liner from port 1 to port p is viewed as a cycle, our method suggests that each port along the line takes some responsibility for every shift undertaken in every port of call. Loading and unloading operations are a port's main profit generator, so they can be used to derive the cost-sharing plan.

In Equation (20), a shift cost for each port p, C_p^S, is used to calculate the total shift cost for the shipping line, C^{total}. Because loading and unloading lists for all ports are determined in advance, the second, third, and forth summations show the total loading and unloading operations for all ports. Then,

$$C^{total} = \sum_{p \in P} C_p^S \times \left\{ n_p^{CO} - \frac{1}{2} \sum_{i \in T} \left(L_p^i + U_p^i \right) - \sum_{i \in F} \left(L_p^i + U_p^i \right) \right\} \tag{20}$$

We then consider the cost-sharing with the ratio of loading and unloading operations in port and total loading and unloading operations in all ports. Target shifting cost for each port q, C_q, is defined in Equation (21).

$$C_q = \frac{\sum_{i\in T}\left(L_q^i + U_q^i\right) + 2\sum_{i\in F}\left(L_q^i + U_q^i\right)}{\sum_{p\in P}\{\sum_{i\in T}\left(L_p^i + U_p^i\right) + 2\sum_{i\in F}\left(L_p^i + U_p^i\right)\}} \times C^{total} \tag{21}$$

A reasonable shift cost is incurred on the basis of the profit generated by loading and unloading operations through the cost-sharing method described above. However, because this method would cause additional shifting costs at certain ports that do not currently have to bear them, conflict could arise between ports. Therefore, we propose another alternative, called *a ratio proportional method*. This method computes a ratio based on the shifting costs generated by a local optimal perspective and distributes the costs generated by a global optimal perspective through this ratio. C_p^O is defined as the shifting cost from a local optimization perspective for each port p. Then the second cost-sharing method for each port q, C_q, is defined as given in Equation (22).

$$C_q = \frac{C_q^O}{\sum_{p\in P} C_p^O} \times C^{total} \tag{22}$$

All ports could bear lower costs, as they were responsible for higher costs under a local optimal perspective. Both methods consider how to distribute the costs in a fair manner. In addition, other cost-sharing methods could perhaps be developed. The cost-sharing mechanism necessitates further research to achieve full cooperation between ports. In the next section, computational experiments based on the mathematical models are shown.

5. Computational experiment and analysis

The MIP model that we developed for this study was run in Xpress-IVE 8.4. All computational experiments were executed on an Intel i3-7100 U CPU, 2.4 Hz, personal computer with 8GB RAM. To check the validation of the mathematical models, computational experiments were conducted on the basis of container-slot shapes. Figure 4 shows two typical bays, Bays I and II. Although these bays have different shapes, they contain the same total number of cells. Bay I is commonly found under the hatch-cover section on a vessel, while Bay II can typically be found over the hatch-cover section. These bays were used for analyzing the ways different shapes affect shifts during the experiments.

Eighteen data sets are created for computational experiments as listed in Table 3. For each data set, different numbers of 20 ft and 40 ft standard containers and foldable containers are required for loading and unloading operations at each port. Information on origin and destination ports and weights for each container is given in advance. Weight, type, and origin and destination ports were randomly generated. Moreover, more than 66% of the cells were filled with containers during trips.

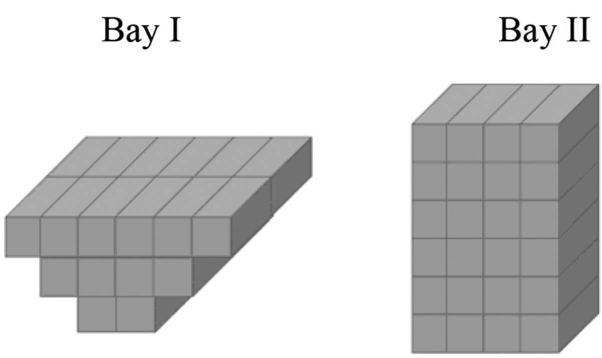

Figure 4. Two different bay types for experiments.

Table 3. Experimental data set.

Data set	Number of containers			Number of ports	Route continuity
	40 ft standard	40 ft foldable	20 ft standard		
1	14	5	18	3	No
2	18	6	26	3	No
3	16	5	18	4	No
4	21	7	34	4	No
5	14	6	8	4	No
6	17	6	24	5	No
7	33	11	42	5	No
8	21	9	18	5	No
9	24	18	20	6	No
10	32	22	12	7	No
11	12	12	24	3	Yes
12	16	14	20	4	Yes
13	25	10	12	5	Yes
14	24	10	4	5	Yes
15	30	12	8	6	Yes
16	42	10	8	6	Yes
17	72	20	28	7	Yes
18	24	24	72	7	Yes

The number of ports varies from three to seven. We also consider continuity in a route to express the real shipping line service of round trips. In the absence of continuity, a shipping liner does not unload at the first port and does not load at the last port. However, in the case of continuity, all ports allow loading and unloading operations. With regard to the stowing constraints of foldable containers, no standard containers, only other foldable containers, can be stowed on top of foldable containers (Section 3). Hence, we assign the first priority to a foldable container to be stowed on top of a standard container. To briefly explain the experimental settings, the higher value of $\frac{|F|+1/2\times|T|}{|p|}$ indicates more short-distance trips in data sets, while the lower value shows more long-distance trips.

We conducted computational experiments with experimental data in Table 3, along with two bay types, Bays I and II, shown in Figure 4 and compared the number of shifts between the global and local optimal perspectives. The global optimal perspective considers all the ports in a dataset for the planning horizon. The key performance indicators, including computation times and numbers of shifts and variables, are provided in Table 4. Each bay is represented by a matrix in computational settings. Because Bay I is not a rectangular shape, there would be a difference in the number of variables between Bays I and II. Please note that computation times were recorded only for the global optimal perspective, with computation times limited to one hour. Because the computation times for the local optimal perspective were completed within a few seconds, they are omitted in the Table

Bay II required significantly longer computation times and more shifts than Bay I. We observe that the number of shifts increase when a stack is deeper and includes data sets with the lower value of $\frac{|F|+1/2\times|T|}{|p|}$, because each port has less free cells, due to containers on long-distance trips being loaded into cells at preceding ports.

In addition, the more ports in a shipping line, the more shifts occur, along with more QC operations required. Although the optimal solutions were not found within one hour for some data sets, we can observe that the number of shifts generated by a global optimal perspective is drastically reduced in comparison to the number generated by a local optimal one. In other words, the best solution from a local optimal perspective is worse than a solution from a global optimal perspective.

With regard to the disadvantage of our mathematical model, computation times can significantly increase, depending on the problem size and number of shifts. An increase in computation times was observed with the large numbers of ports and containers, because the shift problem is NP-complete, while the number of decision variables also increased. It seems that the number of shifts

Table 4. Computation times, numbers of shifts, and numbers of variables for Bays I and II.

	Bay I				Bay II			
		Numbers of shifts				Number of shifts		
Data set	Computation times(sec)	Global	Local	Numbers of variables	Computation times(sec)	Global	Local	Numbers of variables
1	16.4	0	3	15,687	22	0	7	11,631
2	8.1	0	5	21,147	21.9	0	6	15,687
3	95.4	0	5	21,724	101.2	0	16	16,028
4	241.2	0	8	34,420	>1hour	1	12	25,412
5	69.1	0	2	15,652	50.2	3	9	11,540
6	>1hour	1	13	32,393	>1hour	1	24	23,833
7	994.4	0	10	59,069	>1hour	2	20	43,489
8	148.7	0	3	33,077	259.5	3	6	24,337
9	3456.1	0	9	50,886	739.5	0	17	37,374
10	1492.7	0	11	62,911	>1hour	3	13	46,139
11	92.3	0	0	26,692	37.6	6	6	19,700
12	30.4	0	5	34,445	97.6	2	19	25,345
13	>1hour	3	10	38,646	>1hour	13	25	28,374
14	>1hour	2	2	31,302	>1hour	8	29	22,974
15	>1hour	6	12	47,743	>1hour	16	35	35,003
16	>1hour	4	4	57,223	719.7	0	14	41,963
17	27.4	0	11	129,992	769.8	4	18	95,272
18	298.3	0	0	129,992	151.2	6	36	95,272

and computation times show a close relationship with the size of integer-solution space. More rigorous study on the impact of this relationship would be desired in the future. Moreover, the real-world problem encompasses numbers far larger than our sampling size used in this study, and incurs more shifts, so that more ports and containers would need to be considered by developing various solution methods.

Therefore, we proposed an effective way to shorten the planning horizon for one of the solutions to the large-sized problem. For the global optimal perspective, we set the planning horizon over the entire series of ports, but we now reduce it to two ports for a new planning horizon, which we refer to as the *2-port method*. That is, each port establishes a stowage plan considering the loading and unloading operations of the next port. We conducted experiments on Datasets 11–18 with Bay II, considering round-trips, and compared these results with the previous results. All computation times were less than a minute, but they are omitted from Table 5. The efficiency of the 2-port method based on shift generation is defined in Equation (23).

$$\text{Efficiency (\%)} = \frac{\textit{Local optimal} - \textit{2-port method}}{\textit{Local optimal} - \textit{Global optimal}} \tag{23}$$

We observed that the 2-port method drastically reduces the number of shifts. Efficiency improvements of 29%–100% are shown for four sample datasets. Dataset 11 was easy to find

Table 5. Number of shifts for the different planning horizons.

	Number of shifts			
Data set	Global optimal	2-port method	Local optimal	efficiency
11	6	6	6	-
12	2	2	19	100%
13	13	18	25	58%
14	8	23	29	29%
15	6	18	35	59%
16	0	2	14	86%
17	4	8	18	71%
18	6	6	36	100%

optimal solutions in all three methods. In the end, reducing the planning horizon proved effective in solving large-sized problems. In particular, computation times were greatly reduced. Because solutions obtained with the method are not global optimal yet, other methods can be developed as well.

To examine the impact of weight balance on shift generation, we analyzed Datasets 17 and 18, which contain the largest number of containers, as shown in Table 6. The particular value of the weight balance was determined in advance based on the type of vessel. However, as many different types of vessels exist in practice, one can see a certain trend in the impact of foldable containers. We analyzed the number of shifts from decreasing the common difference by 6 tons, starting from 36 tons, but the number of shifts remained the same, and computation times did not show any particular trend.

Thereafter, we calculated the shifting cost for each port using Data Sets 13 and 14 for Bay II, where the largest number of shifts occurred, to analyze the cost-sharing method. In the conventional method, all shifting costs are charged by the port when the shift occurs. Therefore, we calculated the cost based on both optimal perspectives and conducted a comparative study with two cost-sharing methods, as shown in Tables 7 and 8, assuming that each shift costs 200 USD in a port.

In general, total shifting costs decreased for both data sets under the global optimal perspective. As expected, the number of shifts occurring in each port also decreased sharply. For a freight volume proportional method that distributes costs in proportion to the number of loading and unloading operations, a few ports have to bear more costs than in a local optimal case. This would cause complaints and conflicts among ports. To address this issue, another alternative, called a ratio proportional method, was proposed, and it can be seen that the cost borne by each port decreases by the same proportion that the total cost decreases in a global optimal perspective. In particular, the distributed costs are always lower than or equal to those of a local optimal perspective. Therefore, all ports would be satisfied, as no additional charges would be incurred at certain ports as in a freight volume proportional method.

Table 6. Computational time(s) for different cross-equilibrium tolerances.

Datasets and bays		Cross-equilibrium tolerance					
		6	12	18	24	30	36
Dataset 17	Bay 1	66.3	66.9	>1hour	19.4	58.4	27.4
	Bay 2	840.9	1064.4	45.7	28.2	736.3	769.8
Dataset 18	Bay 1	961.7	1352.4	967.1	1072.7	638	298.3
	Bay 2	215.8	133.4	215.2	150.6	147.6	151.2

Table 7. Shifting costs for each port based on a global optimal perspective with two methods and a local optimal perspective (Bay II, Data Set 13).

Method		Port 1	Port 2	Port 3	Port 4	Port 5	Total costs
Global	Freight volume proportional method	$530.61	$477.55	$159.18	$1167.35	$265.31	$2600.00
	Ratio proportional method	$104.00	$624.00	$208.00	$1352.00	$312.00	
Local		$200.00	$1200.00	$400.00	$2600.00	$600.00	$5000.00

Table 8. Shifting costs for each port based on a global optimal perspective with two methods and a local optimal perspective (Bay II, Data Set 14).

Method		Port 1	Port 2	Port 3	Port 4	Port 5	Total costs
Global	Freight volume proportional method	$320.00	$64.00	768.00 USD	64.00 USD	384.00 USD	$1600.00
	Ratio proportional method	$0.00	$110.34	662.07 USD	275.86 USD	551.72 USD	
Local		$0.00	$400.00	$2400.00	$1000.00	$2000.00	$5800.00

Experimental results showed that a larger number of shifts occurred with more ports, deeper stacks, and long-distance trips, and implied practical application, especially in light of the emerging trend in the shipping industry of using gigantic vessels. The risk of increasing shifts could be intensified, as could additional costs and service times, but the cross-equilibrium for ship stability would not seem to be affected significantly. From a shipping company's point of view, the company might be better off operating vessels with shallower stacks for long-distance trips, in order to reduce unnecessary shifts under a local optimal environment. This would be in contrast to operating a vessel with deeper stacks, which could trigger lower shifting costs, according to the analysis of results from Table 4. In this regard, vessel type selection could significantly contribute to efficient operations to manage the generation of shifts that occur along the service route. From a terminal operator's point of view, it is difficult to achieve full cooperation with other ports. However, a collective effort, or 2-port method, could bring about a huge reduction in shifts, along with a reduction in system costs and operation times. Between the two cost-sharing methods, a ratio proportional method seems to be the more convincing method to use in order to achieve efficient management of port terminals.

6. Conclusions

In this study, we developed an efficient stowage plan of loading and unloading operations for a shipping liner by considering foldable containers and shift cost-sharing and our proposed MIP model achieved shift minimization under the global optimum perspective by eliminating an inessential shift. From the local optimal perspective, in which a terminal operator only considers a stowage plan for his or her own port, shifts accumulate as the numbers of tiers used and ports visited increase during vessel transit. The computational experiments showed that most inessential QC operations are effectively removed using the 2-port method. Moreover, shortening the planning horizon to two ports instead of considering the entire series of ports was very effective in dealing with large-sized problems. Thereafter, we could achieve reasonable computation times for practical use. On the other hand, as we used the different bay types, the deeper stack triggered more shifts. However, our algorithm efficiently reduced them. Cross-equilibrium did not greatly affect the number of shifts in our study. In addition, considering the many different types of vessels ordered, vessel owners should be also concerned with the number of shifts when designing vessels. Inefficiently designed bays could adversely affect transport times and lead to unnecessary QC operation costs. On the basis of this study, we expect to see the introduction of foldable containers in more maritime logistics. In addition, the proposed MIP model could be applied to other types of containers with other priorities, such as prioritizing the stowing sequence for heavier loads.

A shift cost-sharing method was developed to achieve fairness among all ports in a shipping line. As few researchers have broached cost-sharing, voices from the industry are needed on the proposed method. Therefore, we investigate the reasons that inessential shifts occur in a port by comparing our model to analyze the effects of both optimal perspectives. We found that identifying exact causes for shifts at one port is difficult; rather, all ports in a shipping line seemingly share joint responsibility for shifts. Thus, we proposed two cost-sharing methods to resolve possible conflicts.

We analyzed the impact of shift cost reduction through the proposed model by using the global optimal perspective, and we proposed a mathematical model and cost-sharing methods to prevent conflicts among ports over additional costs. Because few studies have addressed the problem, this study has meaningful implications for relevant practice and future research.

In addition, future research includes two main aspects. Because we have seen greater effectiveness in shift reduction through the global optimal perspective than under the local optimal one, an efficient heuristic algorithm needs to be developed. The MIP model is effective from the global optimal perspective, but it requires an increase in computation times when foldable containers are taken into account. The 2-port method is able to significantly reduce computation times, but the efficiency performance varies depending on the dataset. Hence, heuristics under the global optimal perspective are highly recommended so heuristic solutions can be obtained within reasonable computation times for large problems. For example, one could develop an evolutionary algorithm such as a genetic algorithm or particle swarm optimization based on the meta-heuristics. These heuristics are remarkably effective when a mathematical model contains a variety of binary or integer decisions.

More extensive research on the cost-sharing method proposed by this study is also required. We acknowledge that various methods can be used to develop contracts between ports and realize that these contracts depend on the specific circumstances of each port. The types of contracts that satisfy ports will vary according to market conditions such as the presence of a monopoly or a high degree of competition. Such a topic is worthy of further study.

Acknowledgments

The authors are grateful for the valuable comments from the editor and anonymous reviewers. This study formed part of my thesis studies for the degree of philosophiae doctor (PhD) at the Seoul National University (SNU), which has been further developed and revised after the completion of my thesis.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) [Grant 2015R1A2A1A15053948].

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