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공학박사학위논문

Effects of Foldable Containers in Maritime Logistics

해운물류에서의 접이식 컨테이너 효과 분석

2022 년 2 월

서울대학교 대학원
산업공학과

김 민 수

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이 논문을 공학박사 학위논문으로 제출함
2021 년 12 월

서울대학교 대학원
산업공학과
김 민 수

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Abstract

Effects of Foldable Containers in Maritime Logistics

Minsu Kim
Department of Industrial Engineering
The Graduate School
Seoul National University

After containerization, maritime logistics experienced the substantial growth of trade volumes and led to globalization and industrial development. However, in proportion to the increase in the volume, the degree of container imbalance also intensified due to the disparity between importing and exporting sizes at ports in different continents. A group of researchers is digging into resolving this ongoing challenge, and a new concept of a container, called a foldable container, has been proposed. Nevertheless, foldable containers are still in the early stage of commercialization, and research on the various effects of using foldable containers seems insufficient yet.

This dissertation considers the possible effects of the introduction of foldable containers. First, we analyze the effect of foldable containers on crane operation and reduce shifts from a global perspective. Second, the effect of using foldable containers in hinterland areas was analyzed by noting that the application of foldable containers on land was different from that of the sea. Finally, we provided new insights into the foldable container under plausible dynamic situations in the shipping industry during the COVID-19 and logistics that have increased since the 2008 financial crisis.

A brief explanation of containerization and foldable containers is introduced in Chapter 1, along with the dissertation's motivations, contributions, and outlines. Chapter 2 examines changes in crane operation when the 'top stowing rule' that can be treated with foldable containers is applied and shows that global optimization is more effective than local optimization. In addition, we suggested the cost-sharing method to deal with fairness issues for additional costs between ports when the global optimization method is fully introduced. Chapter 3 shows that foldable containers in the hinterland have the effect of changing routes in addition to reducing transportation space and analyzes how the results change according to various scenarios and policies. Chapter 4 analyzes the effectiveness of foldable containers for different dynamic situations. Moreover, the managerial insight was derived that the optimal number of foldable containers suitable for each situation can be obtained and responded to leasing policies. Chapter 5 describes the conclusions of this dissertation and discusses future research.

The problem definition and solution methods proposed in this dissertation can be seen as meaningful in both academic and industrial aspects. For academia, we presented real-world problems in the field and suggested ways to solve problems effectively. For industry, we offered solutions through quantification and modeling for real problems related to foldable containers. We expect that industrial development and academic achievement can be achieved together through this dissertation.

Keywords: Foldable containers, container imbalance, container loading, hinterland container transport, dynamic situation, supply chain management

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Chapter 1

Introduction

1.1 Containerization and foldable container

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 5.894m long, 2.348m wide, and 2.376m high, but a *forty-foot equivalent unit* (FEU) refers to a 40-ft container that is 12.031m long, 2.348m wide, and 2.376m high. These types of containers are called *standard containers*. Other types include reefer, open-top, flat rack, tank, bulk, pen, and ventilated containers.

Despite total international trade gradually expanding as a result of worldwide economic growth, the World Trade Organization reported that the trade imbalance between exports and imports had grown because the eastern and western worlds are export- and import-oriented, respectively. For example, according to UN Comtrade Database in 2020[1], trade volumes from the United States to China is 136 billion dollars whereas the volumes from China to the United States is 453 billion dollars. 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.

Foldable containers, 4~6 folded containers in a stack equivalent to the size of a standard container, are considered to be innovative containers and are now starting to be commercialized. These containers can be folded when empty, thereby reducing transportation and storage costs. In particular, Bandara et al.[13] 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. However, their production cost is more expensive, and they need special handling equipment that still requires further commercialization. Konings and Thijs[33] and Konings[32] introduced and analyzed the basic advantages and disadvantages of exploiting foldable containers. After that, many studies about the effects and advantages of foldable containers have been conducted. Shintani et al.[50] analyze the effect of foldable containers on fleet size managements, Wang et al.[58] study ship type decisions that considering foldable containers.

Several companies and institutions are competing for the actual production and commercialization of foldable containers. This is especially the case with Holland Container Innovation (HCI) in the Netherlands and with Korea Railroad Research Institute (KRRI) in the Republic of Korea, which is working hard to standardize and fully commercialize foldable containers. The containers these companies developed are shown in Figure 1.1.

Figure 1.1: Foldable containers currently developed(left: KRRI[2]; right: HCI[5])

1.2 Research motivations and contributions

We believe that foldable containers would act as game changers in maritime logistics. However, research on these containers has not been extensively conducted. Most of the related studies focus on the perspective of saving costs through space reduction driven by the containers. At the same time, the disadvantages of foldable containers involve the high operating costs or handling times. We found that there could be more changes in the policies or rules when foldable containers were fully introduced, and there would be additional positive effects other than simply saving space. In this regard, we considered some critical conditions of the containers. Because they are more expensive in manufacturing and complex in building their structure than regular ones, it was found that a top-stowing rule to be stacked on top of standard containers would be necessary. Interviews on sites were conducted at ports to obtain the relevant information, and we realized that inefficiency was prevailing in optimizing quay crane activities due to local-optimizing operations at ports. Accordingly, we developed a mathematical model and analyzed how effective it is when the crane activities are performed from a global perspective. In addition, we highlighted that planning the crane activities from a global perspective could incur higher costs in some ports. Hence, cost-sharing methods are proposed to solve this problem. Regarding the additional effects of the introduction of foldable containers, we noted that the inland flow of these containers is different from that in the ocean. That is, numerous containers are loaded onto ships and moved together around the ocean on a daily basis. However, in the hinterland, few containers are loaded into a truck and carried individually. Therefore, the small number of containers is transported in each path, and its journey can be changed by using foldable containers. Based on this situation, we analyzed the effects of these containers in the hinterland area. In addition, we also pay attention to fluctuation intensified after the COVID-19. We believe that using these containers can facilitate the relocation of empty ones comparing to using standard containers even when there is a limitation of transport capacity. Thus, we investigated that foldable containers can overcome crises more effectively in various dynamic situations. The main contributions of this dissertation are highlighted as follows:

1. For a container loading problem,
    - We propose the top stowing rule that may occur in case that a foldable container is fully commercialized.
    - A mathematical model and heuristic were developed for quay crane operations to minimize shifts throughout the entire ports.
    - From a global perspective, two methodologies were presented to solve the cost-sharing problem when quay crane activities are optimized.

2. For a foldable container in hinterland problem,
    - We consider the different effects of foldable containers on land and sea. Moreover, we analyzed the minor effect caused by the change of transporting routes.
    - A mathematical model was developed for the effects of foldable containers at a single port, and various scenarios and policies were analyzed through computational experiments.
    - A mathematical model was developed to analyze the effects of foldable containers at multi ports.
3. For a foldable container in the dynamic situation problem,
    - A mathematical model was developed to analyze the effect of foldable containers in dynamic situations under two ports.
    - The effects of the foldable containers were analyzed for various dynamic situations such as shutdown and fluctuations in demand and fleet size.
    - We provided managerial insight that foldable containers can be efficiently commercialized through leasing policy.

1.3 Outline of the dissertation

In this dissertation, we presented three different problems related to foldable containers and layout models in each main chapter. In Chapter 2, We examined the previous studies of foldable containers and container loading problems. To solve the problem of optimizing quay crane operations along with foldable containers, we developed a mathematical model and heuristics. Computational experiments were carried out to analyze the performance of the proposed models, and the cost-sharing methods for each port were also studied. In Chapter 3, we studied the existing literature on the empty container repositioning problem and analyzed the effects of using foldable containers in the hinterland. Furthermore, a mixed-integer programming model was developed to investigate the impacts, and computational experiments were conducted under several policies and scenarios. In Chapter 4, We reviewed previous studies on the operation of empty container management under changing situations. The advantageous cases of using foldable containers are realized through the experiments under various dynamic situations. Thereafter, we provided the managerial insight that foldable containers are more effective in leasing than purchasing and also offered effective strategies for the various stakeholders. Finally, in Chapter 5, we gave concluding remarks and possible future research directions of this dissertation

Chapter 2

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

2.1 Introduction

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[10]. Chen et al. [18] 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 et al.[8] and Ambrosino et al.[7] 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 are not extensively studied for considering the plan of a subsequent port when a preceding port lay out 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.

Moreover, because of trade imbalance, terminal operators struggle 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[65] 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. Foldable container is another state-of-the-art strategy in practice. This container shows a great benefit in transportation and storage. 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 chapter, in a vessel.

In this chapter, 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 chapter is as follows: A literature review on stowage plans and foldable containers is presented in Section 2.2, and Section 2.3 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 2.4. Section 2.5 shows the computational experiments and analyses to provide useful insights and implications. The conclusion of the chapter is presented in Section 2.6.

2.2 Literature review

In this section, we present literature essential to this chapter, based on two main topics: stowage plans and foldable containers. Delgado et al.[20] 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.[20] also presented a constraint programming model for fast optimal stowage at container vessel bays. Moura et al.[44] 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 et al.[7] extended the original optimization model of the master bay plan problem developed by Ambrosino et al.[8] 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.[6] developed new fast MIP model to solve the real size of the problem. Kang and Kim[29] 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[17] investigated impacts on terminal operation in container yard and unproductive moves in the terminal. Dik and Kozan[22] 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 et al.[60] 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 et al.[61] and Pacino et al.[48] 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 [9]. 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[23] 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.[12] through use of extensive computational experiments. Avriel et al.[11] 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 [38]. Monaco et al.[40] 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.[62] 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 et al.[35], 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.[28] 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 Yu [36] 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[41] 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, Koning[32], Moon et al.[43], Moon et al.[42], Basarici and Satir[14], and Goh[26]. Shintani et al.[51] 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 et al.[50] 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[58, 63]. 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 2.1 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.

Table 2.1: Comparison of this research with stowage planning literature

	Mathematical model	Problem characteristics	Perspective type	Rolling horizon	Coordination mechanism
Ambrosino et al. [6]	MIP	Master bay planning with reefers and open-tops	L	-	-
Araujo et al.[9]	-	3D container loading plan	L	-	-
Avriel et al.[12]	BIP	Dynamic slot-assignment for shifts	G	-	-
Avriel et al.[11]	-	The complexity of shift problem	G	-	-
Delgado et al.[20]	IP	Slot planning with reefers	L	-	-
Ding and Chou[23]	-	Shift minimization with heuristics	G	-	-
Kang and Kim[29]	IP	Stowage planning with shift minimization	L	-	-
Moura et al.[44]	MIP	Ship routing with stowage	L	-	-
This dissertation (Chapter 2)	MIP	Stowage planning with foldable containers	G	✓	Shift cost-sharing

"L" represents local optimum and "G" represents global optimum

"-" represents none and "✓" represents covered

2.3 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 2.1. In this chapter, 20ft and 40ft standard containers and 40ft foldable containers can be assigned to cells. Indeed, although another type of container such as 45ft standard or reefer is also utilized in practice, only 40ft foldable container is available up to the present. Thus, these three types would be considered in this chapter 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 2.2.

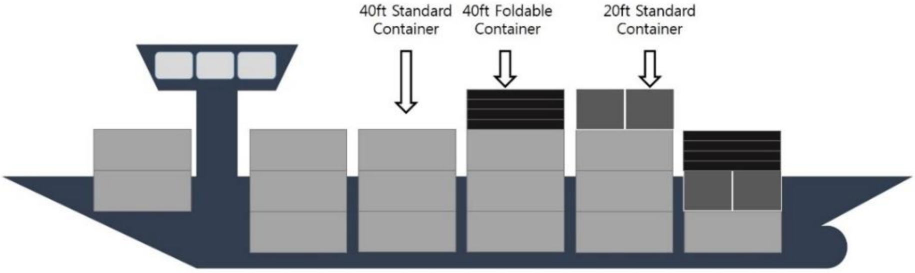


Figure 2.1: Arrangement of container slots on the vessel with 40ft standard and foldable containers and 20ft standard container

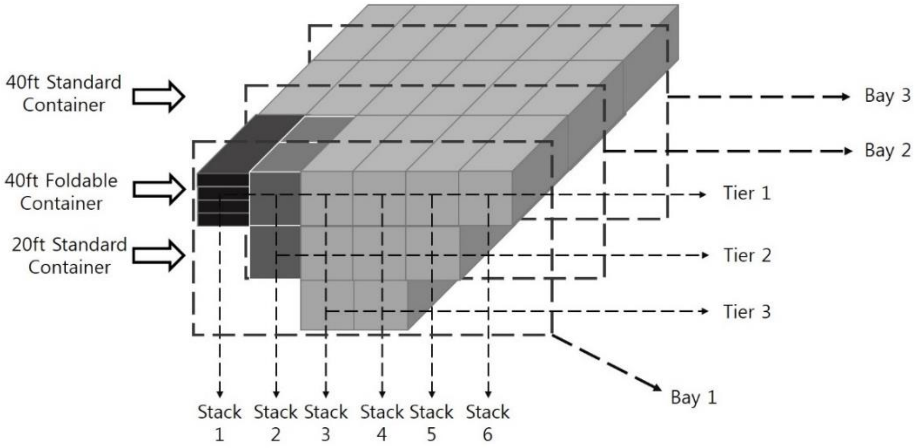


Figure 2.2: Stacks and tiers with 40ft standard and foldable containers and 20ft standard container in a bay

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 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, we provide protection rules for preventing damage from other containers. Therefore, this chapter 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 2.3 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.

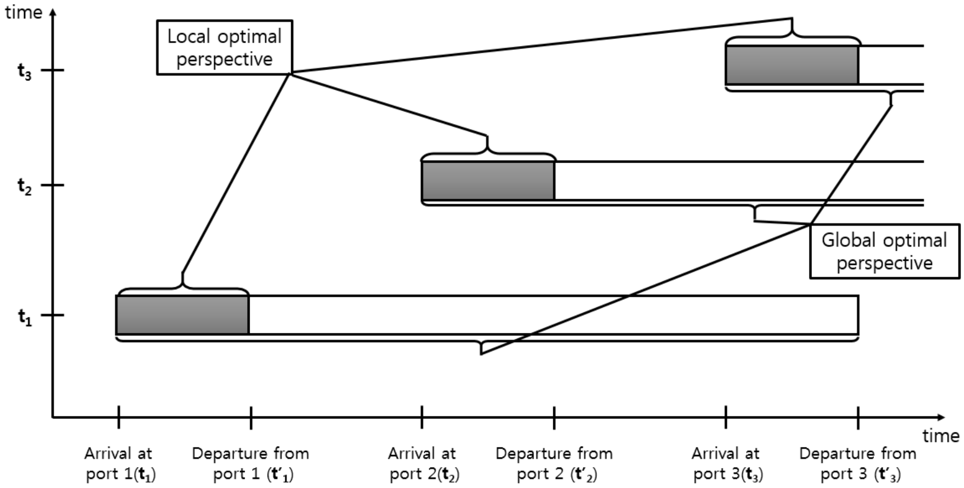


Figure 2.3: The planning horizon at each port from a local optimal perspective (gray area only) and global optimal perspective (gray and white areas)

The ultimate goal of this chapter 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 20ft 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 a bundle of the four containers to be loaded or unloaded on a vessel and independent of QC operations.

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

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

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.

2.4 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.[20]. However, in our model, objective function and constraints related to ship stability and a foldable container, differ from those they used.

2.4.1 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 2.2. 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 and $p + 1$, respectively, to indicate dummy ports. More details on these notations are provided in Table 2.2.

Table 2.2: Parameters, sets, and decision variables in the MIP model

Sets	
I	set of containers, indexed by i
T	set of 20ft standard containers, $T \subset I$
F	set of 40ft 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)

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

minimize
$$\sum_{p\in P} n_p^{CO} \tag{2.1}$$

subject to
$$\frac{1}{2}\sum_{i\in T} c_p^{jkbi} + \sum_{i\in F} c_p^{jkbi} \leq 1 \quad \forall\, p\in P, (k,j,b)\in SC \tag{2.2}$$

$$\sum_{(k,j,b)\in SC} c_p^{jkbi} = \sum_{q=0}^{p}\left(L_q^i - U_q^i\right) \qquad \forall\, i\in I, p\in P\cup\{0\} \tag{2.3}$$

$$\sum_{t\in T} c_p^{jkbt} \geq 2c_p^{jkbi} \qquad \forall i\in T, p\in P, (k,j,b)\in SC \tag{2.4}$$

$$\sum_{k\in K}\sum_{i\in I} w^i c_p^{jkbi} \leq W^j \qquad \forall\, p\in P, (k,j,b)\in SC \tag{2.5}$$

$$\begin{aligned}\frac{1}{2}\sum_{i\in T} o^i c_p^{j(k-1)bi} + \sum_{i\in F} o^i c_p^{j(k-1)bi} \leq{}& \frac{1}{2}\sum_{i\in T} o^i c_p^{jkbi} \\ &+ \sum_{i\in F} o^i c_p^{jkbi} \quad \forall p\in P, (k,j,b)\in SC, k\neq 1\end{aligned} \tag{2.6}$$

$$-Q \leq \sum_{(k,j,b)\in SCR} \sum_{i\in I} w^i c_p^{jkbi} - \sum_{(k,j,b)\in SCL} \sum_{i\in I} w^i c_p^{jkbi} \leq Q \quad \forall p \in P \tag{2.7}$$

$$c_{p-1}^{jkbi} + c_p^{jkbi} - 1 = \alpha_p^{jkbi+} - \alpha_p^{jkbi-} \quad \forall i \in I, p \in P, (k,j,b) \in SC \tag{2.8}$$

$$\alpha_p^{jkbi+} + \alpha_p^{jkbi-} = 1 - n_p^{jkbi} \quad \forall i \in I, p \in P, (k,j,b) \in SC \tag{2.9}$$

$$n_p^{jkb} \leq \sum_{i\in I} n_p^{jkbi} \leq 4n_p^{jkb} \quad \forall\, p \in P, (k,j,b) \in SC \tag{2.10}$$

$$kn_p^{jkb} \leq m_p^{jb} \qquad \forall\, p \in P, (k,j,b) \in SC \tag{2.11}$$

$$m_p^{jb} \geq LC^{jb} - \sum_{\mathrm{k}\in K} \left(\frac{1}{2} \sum_{i\in T} c_{p-1}^{jkbi} + \sum_{i\in F} c_{p-1}^{jkbi} \right) \quad \forall\, p \in P, (k,j,b) \in SC \tag{2.12}$$

$$\begin{aligned} &2 \sum_{b\in B} \sum_{j\in J} \left(m_p^{jb} - \left(LC^{jb} - \sum_{k\in K} \left(\frac{1}{2} \sum_{i\in T} c_{p-1}^{jkbi} + \sum_{i\in F} c_{p-1}^{jkbi} \right) \right) \right) \\ &+ \frac{1}{2} \sum_{i\in T} \left(L_p^i - U_p^i \right) + \sum_{i\in F} \left(L_p^i - U_p^i \right) = n_p^{CO} \quad \forall\, p \in P, (k,j,b) \in SC \end{aligned} \tag{2.13}$$

$$c_p^{jkbi} \in \{0,1\} \quad \forall i \in I, p \in P, (k,j,b) \in SC \tag{2.14}$$

$$n_p^{jkbi} \in \{0,1\} \quad \forall i \in I, p \in P, (k,j,b) \in SC \tag{2.15}$$

$$n_p^{jkb} \in \{0,1\} \quad \forall p \in P, (k,j,b) \in SC \tag{2.16}$$

$$n_p^{CO} \in Z_+ \qquad \forall p \in P \tag{2.17}$$

$$m_p^{jb} \in Z_+ \qquad \forall j \in J, b \in B, p \in P \tag{2.18}$$

$$\alpha_p^{jkbi+}, \alpha_p^{jkbi-} \in \{0,1\} \quad \forall i \in I, p \in P, (k,j,b) \in SC \tag{2.19}$$

The objective function (2.1) 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 (2.2) ensures that at most either a pair of 20ft or single 40ft containers is stowed in a cell. Constraint (2.3) 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 20ft standard containers that must be in a pair is presented in Constraint (2.4). Constraint (2.5) represents the weight limits of stacks necessary for maintaining the stability of a vessel. Constraint (2.6) 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 (2.7). Constraints (2.8) and (2.9) count the number of QC operations. This counting procedure is initiated whenever containers are loaded, unloaded, or shifted. Constraint (2.10) 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 20ft standard container must be paired with another for any operation in this model. Constraint (2.11) locates the lowest cell in a stack in which any container is loaded, unloaded, or shifted at a port. Constraints (2.11), (2.12), and (2.13) are designed to count the total number of QC operations by identifying any movement for inbound and outbound containers in cells. Constraints from (2.14) to (2.19) define decision variables.

Avriel et al.[11] 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.

2.4.2 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 (2.20), 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,

$$C^{total} = \sum_{p \in P} C_p^S \times \left\{ n_p^{CO} - \frac{1}{2} \sum_{i \in T} \left(L_p^i + U_p^i \right) - \sum_{i \in F} \left(L_p^i + U_p^i \right) \right\} \tag{2.20}$$

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 (2.21).

$$C_q = \frac{\sum_{i \in T} \left(L_q^i + U_q^i \right) + 2 \sum_{i \in F} \left(L_q^i + U_q^i \right)}{\sum_{p \in P} \{ \sum_{i \in T} \left(L_p^i + U_p^i \right) + 2 \sum_{i \in F} \left(L_p^i + U_p^i \right) \}} \times C^{total} \tag{2.21}$$

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 (2.22).

$$C_q = \frac{C_q^O}{\sum_{p \in P} C_p^O} \times C^{total} \tag{2.22}$$

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.

2.5 Computational experiment and analysis

The MIP model that we developed for this chapter was run in Xpress-IVE 8.4. All computational experiments were executed on an Intel® Core™ i3-7100U 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 2.4 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.

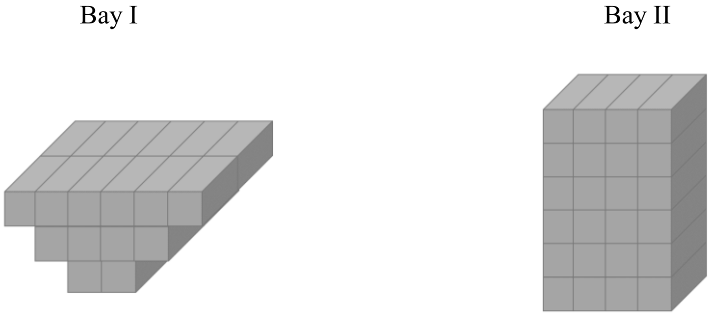


Figure 2.4: Two different bay types for experiments

18 data sets are created for computational experiments as listed in Table 2.3. For each data set, different numbers of 20ft and 40ft 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. 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 2.3). 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.

Table 2.3. Experimental data set

Data set	Number of containers			Number of ports	Route continuity
	40ft standard	40ft foldable	20ft 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

We conducted computational experiments with experimental data in Table 2.3, along with two bay types, Bays I and II, shown in Figure 2.4 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 2.4. 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.

Table 2.4: Computation times, numbers of shifts, and numbers of variables for Bays I and II

Data set	Bay I				Bay II			
	Computation times(sec)	Numbers of shifts		Numbers of variables	Computation times(sec)	Number of shifts		Numbers of variables
		Global	Local			Global	Local	
1	16.4	0	3	15687	22	0	7	11631
2	8.1	0	5	21147	21.9	0	6	15687
3	95.4	0	5	21724	101.2	0	16	16028
4	241.2	0	8	34420	>1hour	1	12	25412
5	69.1	0	2	15652	50.2	3	9	11540
6	>1hour	1	13	32393	>1hour	1	24	23833
7	994.4	0	10	59069	>1hour	2	20	43489

8	148.7	0	3	33077	259.5	3	6	24337
9	3456.1	0	9	50886	739.5	0	17	37374
10	1492.7	0	11	62911	>1hour	3	13	46139
11	92.3	0	0	26692	37.6	6	6	19700
12	30.4	0	5	34445	97.6	2	19	25345
13	>1hour	3	10	38646	>1hour	13	25	28374
14	>1hour	2	2	31302	>1hour	8	29	22974
15	>1hour	6	12	47743	>1hour	16	35	35003
16	>1hour	4	4	57223	719.7	0	14	41963
17	27.4	0	11	129992	769.8	4	18	95272
18	298.3	0	0	129992	151.2	6	36	95272

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 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 chapter, 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 2.5. The efficiency of the 2-port method based on shift generation is defined in Equation (2.23).

$$\text{Efficiency (\%)} = \frac{Local\ optimal - 2\text{-}port\ method}{Local\ optimal - Global\ optimal} \tag{2.23}$$

Table 2.5: Number of shifts for the different planning horizon

Data set	Number of shifts			
	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%

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 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 2.6. 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.

Table 2.6: 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

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 2.7 and 2.8, assuming that each shift costs $200 in a port.

Table 2.7: 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 2.8: 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	\$64.00	\$384.00	\$1600.00
	Ratio proportional method	\$0.00	\$110.34	\$662.07	\$275.86	\$551.72	
Local		\$0.00	\$400.00	\$2400.00	\$1000.00	\$2000.00	\$5800.00

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.

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 2.4. 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.

2.6 Conclusions

In this chapter, 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 chapter, 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.

Chapter 3

Effects of using foldable containers in hinterland areas

3.1 Introduction

With a tremendous increase in world trade in recent years, overseas container traffic also dramatically increased because shipping containers are among the most cost-effective and safe ways to trade. More than 80% of world trade volume involves container shipping [21]. Therefore, research has been widely conducted for effective ocean shipping, and a recent review was offered by Wang and Meng[59]. However, container shipment has drawbacks created by imbalanced trades across regions Theofanis and Boile[56]. For example, in areas where empty containers are in surplus, shipping companies suffer from the high costs of storing many empty containers, while companies in high demand areas need to pay rental or purchase prices to obtain empty containers. As a consequence, over or under supply of empty containers are among the main issues in the container shipping industry[52]. For this reason, shipping companies and researchers have tried to set effective repositioning plans for moving empty containers, and thus, mitigate container supply problems.

Many studies have been conducted to solve empty container repositioning problems since the work of Crainic, Gendreau, and Dejax[19] was published. Shintani et al.[49] introduced a network design for liner shipping. Song and Carter[53] analyzed critical factors affecting empty container repositioning. Dong and Song[24] combined the empty container repositioning problem with a fleet sizing problem. They considered dynamic, uncertain, and imbalanced customer demands. From a different perspective, Song and Dong[54] combined the empty container repositioning problem with a cargo routing problem. Moon, Ngoc, and Hur[43] looked at the multi-port empty container repositioning problem through leasing and purchasing strategies. Braekers, Janssens, and Caris[15] reviewed the repositioning problem at a regional level, and a detailed analysis on different planning levels was conducted. The repositioning problem was extended by considering port disruptions[21]. Lu and Mu[39] examined a slot reallocation model for efficient container transportation. However, researchers examining empty container repositioning have encountered some limitations in terms of the operational and technical aspects. Shortcomings in studies addressing the operational facets of empty container use, even among works that described effective decreases in repositioning costs, showed that operational efforts may not reduce the total volume of empty container flow. In addition, previous studies mainly focused on liner shipping. However, the repositioning issue is not restricted to ocean transportation. For example, empty containers constitute approximately 20% of total container flows, and almost 40% of these containers are associated with land transport [51]. Other container studies, such as Chang et al.[16] and Wang, Lai, and Mohmand[57] also focused on hinterland transportations with port(s). Thus, the importance of empty container repositioning in the hinterland area cannot be overstated.

In terms of technical facets of the repositioning, a new type of container, which is foldable, can be used to substitute for a single standard container of the same volume. Use of foldable containers can effectively reduce the total volume of empty containers. However, only a handful of studies have been conducted on the deployment of the recently developed foldable container. Shintani, Konings, and Imai[50] introduced a fleet management model for liner shipping networks by considering both foldable and standard containers, which motivated our study, and the mathematical model used revealed the optimal mix of using both types of containers in the fleet. Moon, Do Ngoc, and Konings[42] and Moon and Hong[41] compared the repositioning costs when foldable containers were used to those when standard containers were used. Myung and Moon[46] proposed a problem similar to that introduced by Moon, Do Ngoc, and Konings[42] and solved it within polynomial time. Zheng, Sun, and Zhang[66] determined the perceived container leasing prices by looking at different types of containers used at multiple ports. A two stage approach was used to solve the proposed model. Zhang et al.[64] introduced the repositioning problem with foldable containers in an intermodal transportation network. Myung[45] showed that several mathematical models developed by Shintani, Konings, and Imai[51] could be solved within polynomial time.

To our knowledge, Shintani, Konings, and Imai[51] authored the first paper on the use of foldable containers in a single hinterland area for the empty container repositioning problem. Despite analyzing the effects of foldable containers on total costs under different hinterland conditions, Shintani, Konings, and Imai[51] mainly focused on total costs and neither looked into the detailed effect of using foldable containers nor considered simultaneous use of both foldable and standard containers. To fill the research gap addressing the operational and technical aspects of using foldable containers, we systematically analyzed the effects of using foldable containers in the hinterland repositioning problem while taking account of the conditions in which the number of foldable containers was restricted.

The purpose of this chapter is to investigate the effects of using foldable containers in hinterland areas under the assumption that the number of foldable containers is restricted.We analyzed the policies and scenarios related to the hinterland, as studied by Shintani, Konings, and Imai[51]. In general, it has been assumed that foldable containers reduce the cost of transporting empty containers by $^{1}/_{n}$. However, we have found another effect of using foldable containers called a minor effect which can save more money. In addition, we propose a multi-depot model by considering the interaction of the effects of using foldable containers between different hinterland areas, and we reveal that using foldable containers could influence repositioning costs under different conditions. Mathematical models are developed to analyze the fundamental effects of using foldable containers. Experimental results show the properties of foldable containers. We conclude that the effects of using foldable containers can vary significantly according to different hinterland conditions; therefore, the trade-offs between the effects of using foldable containers should be considered.

The remainder of this chapter is as follows: We introduce the single depot repositioning problem (SDRP) in Section 3.2 and expand it to a multi-depot repositioning problem (MDRP) in Section 3.3. Computational experiments are presented in Section 3.4, and Section 3.5 offers conclusions about this chapter.

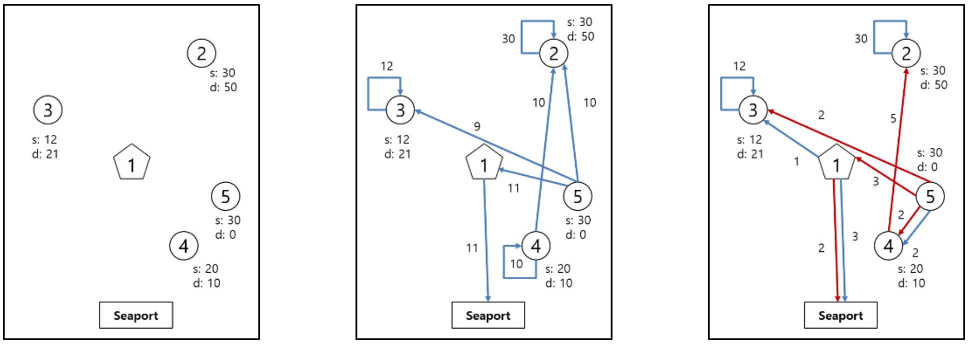
3.2 Single depot repositioning problem

We consider a hinterland repositioning problem in which both standard and foldable containers are used. For the systematic analysis of the effects of using foldable containers, a single depot repositioning problem (SDRP) similar to that proposed by Shintani, Konings, and Imai[51] is described. We present detailed descriptions of the SDRP and introduce the mathematical formulation. Furthermore, we define the effects of using foldable containers and explain different hinterland conditions.

3.2.1 Problem description

For this chapter, a hinterland area was assumed to consist of a seaport, an inland depot, and customer nodes (of shippers and consignees). Each customer node was characterized by the supply and demand of empty containers, and a shipping company needed to satisfy customer requests. If the customers' aggregated supply of empty containers in the identified area was larger than the customers' aggregated demand, then the depot is referred to as the *supply depot.* In the converse situation, the depot is named the *demand depot.* The SDRP was used as an empty container repositioning problem for a supply depot. The geographical details of the hinterland area and the customers' supply and demand information were assumed to be known. In addition, according to a deterministic perspective, the SDRP required a week-long process in the identified area. To satisfy the supply and demand at customer nodes, a shipping company needed to set a plan to reposition empty containers. When a container was moved, transportation and handling costs were incurred. However, when empty containers were reused at the same customer node, transportation costs were not incurred. We defined the sum of transportation and handling costs as *repositioning costs.* Use of foldable containers reduces repositioning costs. The most common type of foldable containers is the four-in-one type in which four foldable containers are used to build a single folded pack that has the same volume as a single standard container. Therefore, the repositioning cost of a folded pack is the same as that of a single standard container. In the case in which fewer than four foldable containers were used, a folded pack was assumed to be unusable because it could not be built safely.

However, use of foldable containers leads to costs not incurred when standard containers are used. Exploitation costs of a foldable container are more than those of a standard container because of higher manufacturing costs. Moreover, additional processes, requiring workers with special tools, are needed to fold and unfold the containers. When a folded pack is built at a node, a folding process is necessary. Likewise, an unfolding process is needed to unfold a folded pack to satisfy the demand for empty containers at a customer node. Both processes incur costs, and we denoted these costs as *folding and unfolding costs.*



(a) Example of a supply depot

(b) Repositioning plan with standard containers

(c) Repositioning plan with mixed containers

Figure 3.1: Example of the SDRP (red arrow: repositioning of folded packs, blue arrow: repositioning of standard containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node)

We considered the case of a restricted number of foldable containers such that a company exploits both standard and foldable containers (mixed containers) for a repositioning plan. Our objective was to minimize total costs through our model. The supply depot and optimal repositioning plans under different conditions are shown in Figure 3.1. When compared to Figure 3.1(b), Figure 3.1(c) shows that using foldable containers could significantly reduce the total volume of moved empty containers in the given area because one folded pack was used as a substitute for multiple standard containers. Moreover, the repositioning directions of empty containers were also dramatically changed after foldable containers were exploited.

3.2.2 Mathematical formulation of the single depot repositioning problem

The assumptions of the mathematical model are as follows:

(1) The supply and demand of empty containers are not the same. The model is based on the presumption of an imbalance of empty containers between supply and demand of each customer node.

(2) The supply and demand of empty containers for each customer node are deterministic and known.

(3) The number of foldable containers in a depot is limited to reflect the realistic condition that foldable containers are not typically evenly distributed.

(4) Folded packs cannot be reused at a customer node as folded because they need to be unfolded to be used.

(5) Four-in-one foldable containers are used in the area, and a folded pack should be made of four containers to maximize cost savings for each folded pack and to fit the standard size for shipping.

(6) Foldable packs can be passed through the inland depot to other nodes; however, folded packs should be used in a customer node.

(7) The sizes of containers are assumed to be homogeneous; the size of a foldable container and that of a folded pack are the same as that of a standard container.

(8) The folding and unfolding costs are assumed to be the same.

(9) The repositioning costs, including transportation and handling expenses, are the same regardless of the types and states of empty containers.

(10) The number of available foldable containers in the hinterland area is given. Notations are provided in Table 3.1.

Table 3.1: Sets, indices, parameters, and decision variables in the SDRP model

Set and indices	
N	set of nodes including a seaport, an inland depot, and customer nodes
i, j	indices of nodes, $\forall i, j \in N$
0	index of a seaport
1	index of an inland depot
Parameters	
s_i	supply of empty containers at node $i, \forall i \in N \backslash \{0,1\}$
d_i	demand of empty containers at node $i, \forall i \in N \backslash \{0,1\}$
A	number of available foldable containers at the hinterland area
c^{FU}	folding and unfolding costs
$c_{i,j}^{R}$	repositioning costs to move containers from i to $j, \forall i, j \in N$
F	required number of foldable containers to build a folded pack
Decision Variables	
$x_{i,j}^{F}$	number of folded packs moved from node i to node $j, \forall i, j \in N$
$x_{i,j}^{U}$	number of unfolded foldable containers moved from node i to node $j, \forall i, j \in N$
$x_{i,j}^{S}$	number of standard containers moved from node i to node $j, \forall i, j \in N$
z_i	number of folded and unfolded processes at node $i, \forall i \in N \backslash \{0\}$

The proposed mathematical formulation of the SDRP is as follows:

minimize
$$\sum_{i,j \in N} c_{i,j}^{R}(x_{i,j}^{F} + x_{i,j}^{U} + x_{i,j}^{S}) + \sum_{i \in N \backslash \{0\}} c^{FU} z_i \tag{3.1}$$

subject to
$$\sum_{j \in N} (F x_{i,j}^{F} + x_{i,j}^{U} + x_{i,j}^{S}) = s_i \forall i \in N \backslash \{0,1\} \tag{3.2}$$

$$\sum_{i\in N}\left(Fx_{i,j}^{F}+x_{i,j}^{U}+x_{i,j}^{S}\right)=d_j \quad \forall j\in N\backslash\{0,1\} \tag{3.3}$$

$$\sum_{i\in N}(Fx_{1,i}^{F}+x_{1,i}^{U})=\sum_{i\in N}(Fx_{i,1}^{F}+x_{i,1}^{U}) \tag{3.4}$$

$$\sum_{i\in N}x_{1,i}^{S}=\sum_{i\in N}x_{i,1}^{S} \tag{3.5}$$

$$\sum_{i\in N\backslash\{0,1\}}\sum_{j\in N}(Fx_{i,j}^{F}+x_{i,j}^{U})=A \tag{3.6}$$

$$z_1=F|\sum_{j\in N}x_{1,j}^{F}-\sum_{j\in N}x_{j,1}^{F}| \tag{3.7}$$

$$z_i=F\sum_{j\in N}(x_{i,j}^{F}+x_{j,i}^{F})\forall i\in N\backslash\{0,1\} \tag{3.8}$$

$$x_{i,i}^{F}=0 \quad \forall i\in N \tag{3.9}$$

$$x_{i,i}^{U}=x_{i,i}^{S}=0 \quad \forall i\in\{0,1\} \tag{3.10}$$

$$x_{0,i}^{F}=x_{0,i}^{U}=x_{0,i}^{S}=0 \quad \forall i\in N\backslash\{0\} \tag{3.11}$$

$$x_{i,0}^{F}=x_{i,0}^{U}=x_{i,0}^{S}=0 \quad \forall i\in N\backslash\{0,1\} \tag{3.12}$$

$$x_{i,j}^{F},x_{i,j}^{U},x_{i,j}^{S}\in\mathbb{Z}_{+} \quad \forall i,j\in N \tag{3.13}$$

$$z_i\in\mathbb{Z}_{+} \quad \forall i\in N\backslash\{0\} \tag{3.14}$$

The objective function (3.1) minimizes total costs, including those for repositioning as well as folding and unfolding containers, in a hinterland area. Constraints (3.2) and (3.3) suggest that the supply and demand of empty containers for each customer node should be satisfied. Constraints (3.4) and (3.5) refer to balance equations in an inland depot. Constraint (3.6) sets the limits of the restricted number of foldable containers in the hinterland area. Constraint (3.7) counts the difference between the inflows and outflows of folded containers at an inland depot, which is the same as the number of necessary folding and unfolding processes. Constraint (3.8) denotes every inflow (outflow) of folded packs needed to be unfolded (folded) to meet the demand (supply) of Node i. Constraint (3.9) ensures that reused empty containers cannot be in the folded state. Constraint (3.10) ensures that containers cannot be reused at an inland depot and seaport. Constraints (3.11) and (3.12) restrict that empty containers cannot directly move from customers to the seaport. In addition, containers cannot move from a seaport to an inland depot. Constraints (3.13) and (3.14) guarantee that all variables are nonnegative integers. The number of constraints increases in direct proportion to the number of nodes.

3.2.3 Effects of foldable containers

The main advantage of using foldable containers is to reduce repositioning costs without changes to the original repositioning plan. However, it does not mean that the effects from using foldable containers are restricted to this case. As presented in Figure 3.1, foldable containers can be used in changed repositioning directions to reduce costs further. Therefore, systematic analysis is necessary to explain the unique characteristics of using foldable containers from an operational perspective. We illustrate fundamental features of foldable containers. We also define and present different effects of using foldable containers, including those found under different hinterland conditions.

As mentioned in the problem description, the main feature of foldable containers is that several can be folded to build a single folded pack. The major effects of using foldable containers are seen when a sufficient number of foldable containers are moved between nodes. Folded packs can be built through the folding process in nodes with specific numbers of foldable containers. Likewise, when the packs arrive at a customer node, unfolding processes are required to use the foldable containers. When passed through an inland depot, folded packs do not need to undergo unfolding processes. In addition, when they arrive at a seaport, unfolding processes are not needed because folded packs are moved to other hinterland areas.

We define these advantages as *major effects*.

The other advantageous effects are defined as *minor effects*, which reflect distinctive characteristics of using foldable containers. When the number of foldable containers in a node is less than F, a folded pack cannot be made the ordinary way. In this case, a new strategy is required to build a folded pack; additional containers can be supplied by decreasing the number of reused empty containers. In this case, the same number of empty containers is supplied from other nodes to compensate for the fewer number of reused containers. This process seems illogical because reused empty containers do not incur transportation costs while containers supplied from other nodes are subject to additional transportation costs. However, when foldable containers are exploited, cost savings created by building a folded pack may outweigh additional costs such that total costs can be reduced. Use of foldable containers could affect shippers and the consignees in relatively minor ways. The *first minor effect* is defined when empty containers are supplied to a destined customer node for building an additional folded pack. Empty containers can also be supplied by other nodes for building a folded pack, and this minor effect is denoted as the *second minor effect*.

Figure 3.2 shows a detailed example of the ways use of foldable containers can affect transport. For simplification, the example is based on the assumption that all containers are foldable and F is equal to 4. The arrow from inland depot 1 to Node 2 demonstrates a major effect. The arrow between inland depot 1 and Node 3 illustrates a minor effect. With a similar effect, the folded pack from Node 4 to inland depot 1 is available after Node 5 supplies an empty container to Node 4.

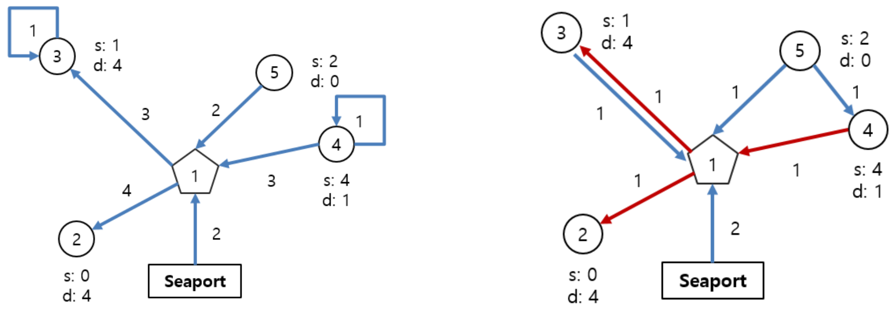
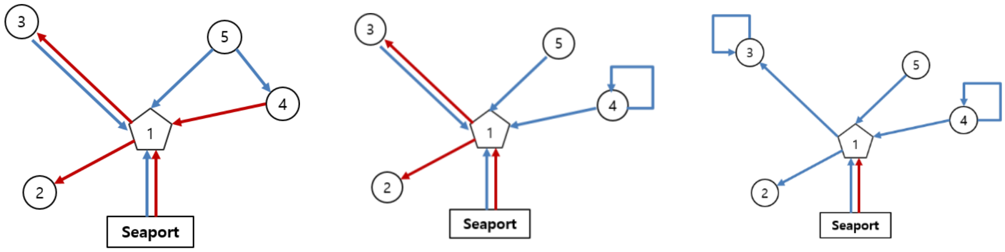


Figure 3.2: The effects of using foldable containers (red arrow: flow of folded packs, blue arrow: flow of unfolded containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node)

Shintani, Konings, and Imai[51] introduced different conditions of the hinterland area. Specifically, cases corresponding to three local repositioning scenarios are advanced direct interchange (ADI), advanced indirect interchange (AII), and simple indirect interchange (SII), and three policies explain use of an inland depot: repositioning and returning via an inland depot (BASIC), repositioning and returning via a seaport (SEAPORT), and repositioning and returning via inland depot or seaport (FLEX). We describe these conditions to explain the work of Shintani, Konings, and Imai[51] and present the ways these main characteristics and conditions influence the effect of using foldable containers. Local repositioning scenarios can be classified by the conditions of customer trade and use of foldable containers. Compared to other scenarios, in the most flexible case, ADI, empty containers can be freely interchanged between customer nodes and an inland depot. Each customer node is presumed to have workers with equipment for folding and unfolding processes. AII repositioning does not permit trade of empty containers between customer nodes, which means that each customer node can satisfy demand

and supply only through an inland depot. In other words, customers use indirect interchange to satisfy demand for and supply of empty containers. Although it increases the total distances of repositioning empty containers between customer nodes, this scenario offers opportunities to centralize empty containers at an inland depot for easy controllability. SII is useful for handling more restricted cases. Under SII, folding and unfolding processes are only conducted at an inland depot. Therefore, folded packs cannot be built in customer nodes. Foldable containers can only be used between a seaport and an inland depot. Detailed examples of these scenarios are illustrated in Figure 3.3.

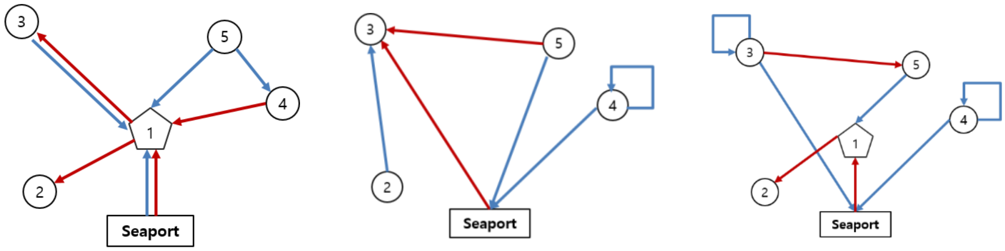
The effects of using each folding processes differ. Unlike ADI, through each customer can directly trade empty containers, AII does not permit movement of empty containers between customer nodes. For this reason, the second minor effect does not occur (i.e., containers cannot be procured directly from other customers). However, in this case, the first minor effect still transpires because empty containers can be exchanged between customer nodes and an inland depot. In the case of SII, like AII, empty containers can be exchanged, but the unfolded packs cannot be built in customer nodes. Therefore, under SII, all minor effects are eliminated, and because the folded packs can be used only between an inland depot and a seaport, this scenario influences the major effects of using foldable containers.



(a) Example of ADI (b) Example of AII (c) Example of SII

Figure 3.3: Different scenarios (red arrow: flow of folded packs, blue arrow: flow of unfolded containers)

Shintani, Konings, and Imai[51] presented three different policies with respect to operating an inland depot. The examples of these policies are illustrated in Figure 3.4. The BASIC policy, which is the basis of our mathematical model, directs all repositioning and returning of empty containers, stacked temporarily at an inland depot and seaport, only through an inland depot. The SEAPORT policy, which does not have an inland depot, allows those in customer nodes to trade empty containers with a seaport. FLEX is the most versatile policy; it permits nodes to send empty containers to a seaport and an inland depot without any restriction. In short, FLEX is the combination of BASIC and SEAPORT; however, we did not consider the policy because it might offset the effects of use of an inland depot and thus prevent a proper analysis of the fundamental effects of using foldable containers. Aggregation of foldable containers confers the main advantage of an inland depot because they can be used to build folded packs on site. We define the savings created by storage and pack building as *aggregation savings*. In contrast to savings, the inland depot could cause unnecessary transportation costs because customers in nodes cannot directly trade empty containers at a seaport. Although in theory the absence of an inland depot decreases transportation costs to a seaport, the increased distances between customers, without permitted direct trade of empty containers, means an increase in transportation costs. In the case of disallowed direct trades but an accessible inland depot, use of folded packs can save on expenses, and we define these savings as *long distance savings*. Therefore, existence of an inland depot can affect the total benefits of using foldable containers, and the trade-off between savings and transportation costs is an importance issue.



(a) Example of BASIC (b) Example of SEAPORT (c) Example of FLEX

Figure 3.4: Different policies (red arrow: flow of folded packs, blue arrow: flow of unfolded containers)

In this chapter, we seek to analyze the fundamental effects of using foldable containers under various conditions. The proposed model covers all combinations of three scenarios and two policies with simple modifications in the formulations. The case of ADI scenario under the BASIC policy is assumed to follow the basic formulation. To consider the case of AII, the following additional constraints are needed:

$$x^F_{i,j} = x^U_{i,j} = x^S_{i,j} = 0 \quad \forall i,j \in N\backslash\{0,1\}, i \neq j \qquad (3.15)$$

To analyze the case of SII, more constraints were required, such as

$$x^F_{i,1} = x^F_{1,i} = 0 \quad \forall i \in N\backslash\{0,1\} \qquad (3.16)$$

From the perspective of the mathematical formulation, the difference between BASIC and SEAPORT is the existence of an inland depot. Therefore, the modification is simple.

3.3 Multi-depot repositioning problem

In this section, we introduce the mathematical formulation for the defined MDRP. Because of the imbalance of world trade, some depots must handle surplus empty containers and others suffer from deficiency of empty containers. Those needing to satisfy shortages of demand depots would benefit from receiving empty containers from supply depots than buying or leasing them at demand depots. We consider a situation in which a single supply depot can send empty containers to multiple demand depots. The example of the MDRP is explained in Figure 3.5.

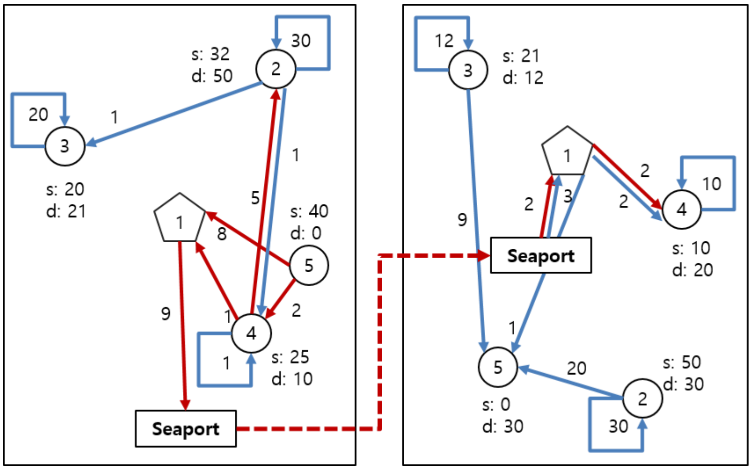
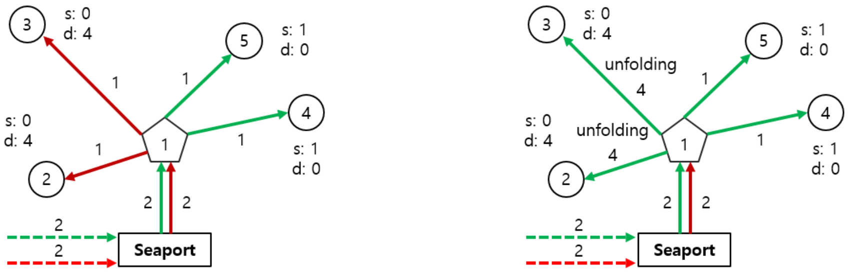


Figure 3.5: Example of the MDRP (red arrow: flow of folded packs, blue arrow: flow of unfolded containers, dotted arrow: shipped containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node)

If each depot exploits one type of containers by using only standard or only foldable containers, the MDRP is easy. Because the supply and demand of empty containers in each depot are deterministic and known, a supply (deficient) depot can send (receive) empty containers to (from) each demand (supply) depot in a non-decreasing cost order. However, when depots use both types of containers, the situation can be more complex. For example, when the number of foldable containers is not sufficient at a demand depot, shipped foldable containers from a supply depot can be used at the demand depot that needs them. In this case, foldable containers help reduce transportation costs, including those for shipment between depots. However, if the number of foldable containers is sufficient at the demand depot, surplus foldable containers could lead to additional costs. Moreover, scenarios and policies in each depot can affect expenses.



Example of a demand depot under AII Example of a demand depot under SII

Figure 3.6: Different effects of foldable containers between demand depots (red arrow: flow of folded packs, green arrow: flow of unfolded containers, dotted arrow: flow of shipped containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node)

Examples are presented in Figure 3.6, which shows the assumption that depots are identical but hinterland scenarios differ. Each demand depot receives the same number of foldable containers from a supply depot. The depot under AII can exploit folded packs; hence, folded packs are moved to nodes. However, an inland depot under SII needs to unfold folded packs because customer nodes cannot unfold them, and this necessity creates unfolding costs. Therefore, in the MDRP, the shipment of foldable containers between depots is an important issue.

Although the MDRP follows the same assumptions used to define the SDRP, additional assumptions to describe the relationships between depots are required. These assumptions are introduced as follows:

(1) A shipping company considers repositioning empty containers between a single supply depot and multiple demand depots.

(2) The aggregated supply and demand of hinterland customers are assumed to be the same. In real cases, this assumption might not be true. However, another assumption would be inappropriate for our model. When the total supply of empty containers is less than the total demand, the company considers purchasing or leasing empty containers to satisfy the demand. The place to purchase or lease empty containers is hence predetermined because the company tries to handle the problem at the lowest cost, and this action does not affect the solution of the proposed model.

(3) The demand depots can utilize shipped containers from a supply depot. (6) Foldable packs can be passed through the inland depot to other nodes; however, folded packs should be used in a customer node.

Sets, parameters, and variables for the SDRP are expanded by multiple depots. The modified descriptions from the single depot problem are not repeated. Additional notations are provided in Table 3.2.

Table 3.2: Additional sets, indices, parameters and decision variables in the MDRP model

Set and indices	
P	set of depots
p	index of a depot, $\forall p \in P$
s	index of a supply depot
N_p	nodes in depot p, $\forall p \in P$
Parameters	
c_p^E	shipping costs between depot s and depot p, $\forall p \in P \backslash \{s\}$
A_p	number of available foldable containers in depot p, $\forall p \in P$
Decision Variables	
y_p^F	number of folded packs shipped from depot s to depot p, $\forall p \in P \backslash \{s\}$
y_p^U	number of unfolded foldable containers shipped from depot s to depot p, $\forall p \in P \backslash \{s\}$
y_p^S	number of standard containers shipped from depot s to depot p, $\forall p \in P \backslash \{s\}$

The formulation of the MDRP is as follows:

$$\text{minimize} \quad \sum_{p \in P} \left[\sum_{i,j \in N_p} c_{i,j,p}^R \left(x_{i,j,p}^F + x_{i,j,p}^U + x_{i,j,p}^S \right) + \sum_{i \in N_p} c_p^{FU} z_{i,p} \right] + \sum_{p \in P \backslash \{s\}} c_p^E \left(y_p^F + y_p^U + y_p^S \right) \tag{3.17}$$

$$\text{subject to} \quad \sum_{j \in N_p} \left(F x_{i,j,p}^F + x_{i,j,p}^U + x_{i,j,p}^S \right) = s_{i,p} \forall i \in N_p \backslash \{0,1\}, \forall p \in P \tag{3.18}$$

$$\sum_{i \in N_p} \left(F x_{i,j,p}^F + x_{i,j,p}^U + x_{i,j,p}^S \right) = d_{j,p} \forall j \in N_p \backslash \{0,1\}, \forall p \in P \tag{3.19}$$

$$\sum_{i\in N_p} (Fx_{1,i,p}^F + x_{1,i,p}^U) = \sum_{i\in N_p} (Fx_{i,1,p}^F + x_{i,1,p}^U)\forall p \in P \tag{3.20}$$

$$\sum_{i\in N_p} x_{1,i,p}^S = \sum_{i\in N_p} x_{i,1,p}^S \forall p \in P \tag{3.21}$$

$$\sum_{i\in N_p\backslash\{0,1\}} \sum_{j\in N_p} (Fx_{i,j,p}^F + x_{i,j,p}^U) = A_p \forall p \in P \tag{3.22}$$

$$\sum_{i\in N_p} (Fx_{1,i,p}^F + x_{1,i,p}^U) \geq Fy_p^F + y_p^U \forall p \in P\backslash\{s\} \tag{3.23}$$

$$x_{i,i,p}^F = 0 \forall i \in N_p, \forall p \in P \tag{3.24}$$

$$x_{i,i,p}^U = x_{i,i,p}^S = 0 \forall i \in \{0,1\}, \forall p \in P \tag{3.25}$$

$$z_{1,p} = F|\sum_{j\in N_p} x_{1,j,p}^F - \sum_{j\in N_p} x_{j,1,p}^F| \forall p \in P \tag{3.26}$$

$$z_{i,p} = F\sum_{j\in N_p} (x_{i,j,p}^F + x_{j,i,p}^F) \forall i \in N_p\backslash\{0,1\}, \forall p \in P \tag{3.27}$$

$$\sum_{p\in P\backslash\{s\}} y_p^F = x_{1,0,s}^F \tag{3.28}$$

$$\sum_{p\in P\backslash\{s\}} y_p^U = x_{1,0,s}^U \tag{3.29}$$

$$\sum_{p\in P\backslash\{s\}} y_p^S = x_{1,0,s}^S \tag{3.30}$$

$$y_p^F = x_{0,1,p}^F \forall p \in P\backslash\{s\} \tag{3.31}$$

$$y_p^U = x_{0,1,p}^U \forall p \in P\backslash\{s\} \tag{3.32}$$

$$y_p^S = x_{0,1,p}^S \forall p \in P\backslash\{s\} \tag{3.33}$$

$$x_{0,i,p}^F = x_{0,i,p}^U = x_{0,i,p}^S = 0 \forall i \in N_p\backslash\{0,1\}, \forall p \in P \tag{3.34}$$

$$x_{i,0,p}^F = x_{i,0,p}^U = x_{i,0,p}^S = 0 \forall i \in N_p\backslash\{0,1\}, \forall p \in P \tag{3.35}$$

$$x_{0,1,s}^F = x_{0,1,s}^U = x_{0,1,s}^S = 0 \tag{3.36}$$

$$x_{1,0,p}^F = x_{1,0,p}^U = x_{1,0,p}^S = 0 \forall p \in P\backslash\{s\} \tag{3.37}$$

$$x_{i,j,p}^F, x_{i,j,p}^U, x_{i,j,p}^S \in \mathbb{Z}_+ \forall i,j \in N_p \tag{3.38}$$

$$y_p^F, y_p^U, y_p^S \in \mathbb{Z}_+ \forall p \in P\backslash\{s\} \tag{3.39}$$
$$z_{i,p} \in \mathbb{Z}_+ \forall i \in N_p \tag{3.40}$$

The objective function (3.17) minimizes the total costs between depots including transportation costs, folding and unfolding costs, and shipment costs between depot s and depot p. Constraints (3.18) and (3.19) denote the supply and demand conditions of empty containers. Constraints (3.20) and (3.21) show the inflow and outflow of empty containers at an inland depot should be equal. Constraint (3.22) explains the restricted number of foldable containers for each node at depot p. Constraint (3.23) denotes the number of foldable containers received at a demand depot. Constraints (3.24) and (3.25) ensure that reused empty containers are not in the folded state. Constraints (3.26) and (3.27) refer to the number of folding and unfolding processes. Constraints (3.28), (3.29), and (3.30) denote the shipped empty containers sent to demand depots that came from supply depot s. Constraints (3.31), (3.32), and (3.33) ensure the number of empty containers move from a seaport to an inland depot. Constraints (3.34) and (3.35) explain that empty containers cannot directly move between a seaport and customer nodes. Constraint (3.36) denotes that the supply depot cannot receive empty containers from demand depots. Constraint (3.37) denotes that demand depots cannot send empty containers to the supply depot. The other constraints explain that all variables are nonnegative integers. The number of constraints increases with the number of nodes and the number of ports.

3.4 Computational experiments

We conducted systematic analyses of impacts of using foldable containers under various conditions. Experimental designs and results of experiments are presented in this section. The models were implemented using XPRESS-IVE 7.9 with the

XPRESS-MP mathematical programming solver, and algorithms were coded in Java 1.8.071 language with the XPRESS-MP library. Experiments were conducted with an Intel® Core™ i5-3570 CPU 3.4 GHz with 8.0 GB of RAM in Windows 10.

3.4.1 Experimental design for the SDRP

Because this chapter is the extended work of Shintani, Konings, and Imai[51], experimental designs and parameter values referred to the previous work. Detailed information of a supply depot is shown as follows in which EC is empty container, EF stands for empty foldable containers, and ES refers to empty standard container.

Table 3.3: Parameter settings were used for experiments

Total supply and demand of EC	160 EC/week
Ratio between supply and demand	9:7
Number of nodes	6 nodes including a seaport and an inland depot
Repositioning cost per EC (Euros)	1.45 · kilometers + 105 + 40 ($i \neq j$), and 0 ($i = j$)
Folding and unfolding costs	40 Euros/EC/Process
Exploitation cost	14/EF, 7/ES

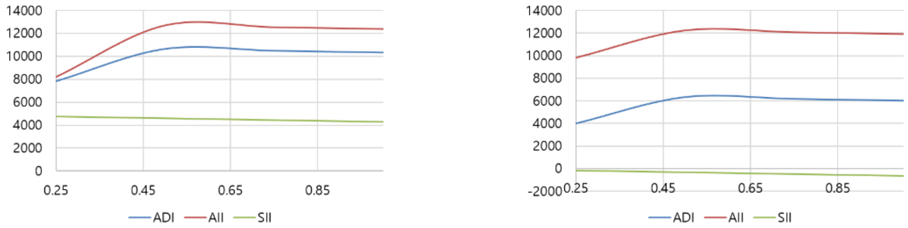
Experiments were conducted with a limited size sample because different effects can be combined together, and they can be extremely complex to interpret in large samples. 6 nodes were randomly generated in 300 square kilometers, and supply and demand were also randomly generated between 1 to 40. In Subsection 3.2.3, three scenarios and two policies of the hinterland area were introduced. Therefore, total six combinations were examined for analysis. Total costs were checked to analyze differences between hinterland conditions. However, these costs do not fully reflect the effects of using foldable containers, which also depend on hinterland conditions. Therefore, differences between total costs with mixed containers and those with only standard containers were measured to calculate cost savings from use of foldable containers. Note that when foldable containers are exploited, additional costs are incurred: (exploitation cost of a foldable container − exploitation cost of a standard container) × number of foldable containers. Values for the effects of using foldable containers (i.e., major and minor effects) were calculated, and sensitivity analyses were conducted to understand the intrinsic properties of the effects of using foldable containers.

3.4.2 Experimental results for the SDRP

To analyze the sequential effect of foldable containers rather than replacing all containers with foldable containers, we use the ratio between standard and foldable containers, α is defined as follows:

$$\alpha = \frac{\text{Number of available foldable containers}}{\text{Aggregated supply and demand of empty containers in a depot}}$$

Figure 3.7 presents the differences between the total cost savings incurred for each container combination and exploitation ratio when using standard containers and when using mixed containers. We graphically plotted the changes in costs in the BASIC and SEAPORT policies for three scenarios: ADI, AII, and SII. The α value was changed from 0.25 to 1 at intervals of 0.25. As explained by Shintani, Konings, and Imai[51], substituting foldable containers for all standard containers could save on total costs substantially. In our experimental results, the total cost savings also decreased by exploiting foldable containers, except for cases in the SII under the SEAPORT policy. In situations where foldable containers can be used, the effect appeared even if only some of them were replaced. However, our results showed that foldable containers were not necessarily needed when α was greater then 0.5, and a surplus of foldable containers could increase total costs. We also observed that the optimal number of foldable containers and the effects of using foldable containers varied by scenarios and policies.



Difference between the save on total costs using standard containers and those when using mixed containers with BASIC

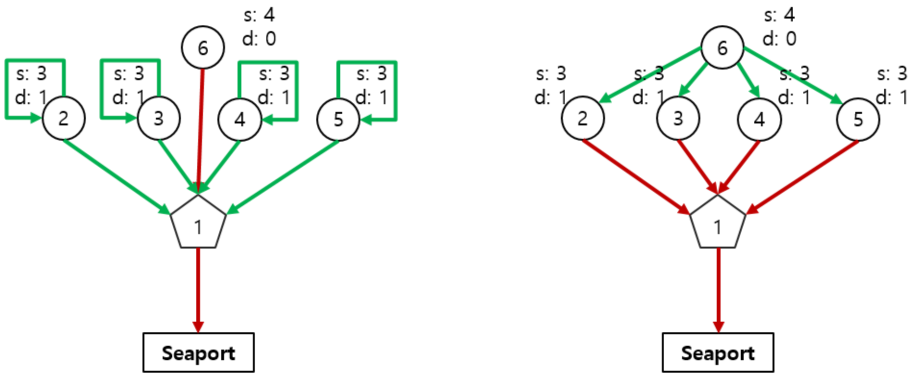
Difference between the save on total costs using standard containers and those when using mixed containers with SEAPORT

Figure 3.7: Relationship between the exploitation ratio (x-axis) and the total cost savings (y-axis, \$) in different scenarios under BASIC and SEAPORT policies

Among cases under the BASIC policy, AII showed the highest optimal number of foldable containers and the greatest cost savings (≃ 12,700). However, SII had the lowest optimal number of foldable containers and least cost savings (≃4,760). In a notable finding, the optimal value of α for the ADI under the BASIC policy was almost the same as it was for AII. However, the cost saving for ADI (≃10,700) was less than that found for AII under the BASIC policy. Under the SEAPORT policy, for AII, the optimal number of foldable containers was relatively low; however, the cost saving was the greatest (≃12,300) among the scenarios. For the ADI under the SEAPORT policy, the cost savings was approximately 6,400, which was less than that found under BASIC policy. In the most distinctive finding with the SEAPORT policy, use of foldable containers in the SII scenario tended to show greater costs than it did in the other scenarios.

3.4.3 Major and minor effects with the single depot repositioning problem

We conducted detailed analyses on major and minor effects of using foldable containers. To evaluate the quantitative values of major and minor effects, we first calculated the value of major effects. Without considering minor effects, the value of the major effects can be easily calculated because when present, they do not change the direction for repositioning empty containers. However, this value might not be the same as that of the proposed model because minor effects could cause a change in repositioning direction.



An example considering only major effects An example considering both effects

Figure 3.8: Different repositioning plans considering the major effects (left) and both effects (right) (red arrow: flow of folded packs, green arrow: flow of unfolded containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node)

An example is illustrated in Figure 3.8. Despite this discrepancy, the experiment still provided an upper bound for the value of the major effects. Thus, cost savings caused by using folded packs without changing direction were used as values of major effects, and they were defined as *Bound*. Cost savings determined by considering both major and minor effects were defined as *Best*.

Effects of using foldable containers under different policies with specific values are challenging to compare because the conditions for each are different. Therefore, relative values were calculated, and we defined relative savings (RS) as the difference of costs between use of standard containers and both types divided by the total costs: (total costs of only standard containers − total costs of both containers)/ total costs of exploiting only standard containers. We first found the optimal exploitation ratio for each case and calculated RS using the optimal α value. Table 3.4 summarizes RS under different effect conditions. We obtained the Bound for different scenarios and policies considering only the major effect. The Best was calculated considering both the major and minor effects. The result showed that cost savings by major effects were significant compared to additional cost savings by applying minor effects. Cost savings by major effects under the BASIC policy outweighed those under the SEAPORT policy in all scenarios. In contrast, differences between additional cost savings found when considering all effects were negligible between policies. The gap between both policies for AII was relatively small because the additional aggregation savings for BASIC and the longer distance savings for SEAPORT were small.

Table 3.4: Relative Savings (%) of Bound and Best for different scenarios and policies

Scenario	Policy	Bound	Best
ADI	BASIC	41.56	43.66
	SEAPORT	31.19	34.17
AII	BASIC	44.43	45.85
	SEAPORT	42.90	43.95
SII	BASIC	17.10	17.10
	SEAPORT	0.00	0.00

For different scenarios and policies, we checked the α value to calculate the number of foldable containers required in order to incur minimum costs, as shown in Table 3.5. In the case of BASIC, the α values of Bound (i.e., at the upper bound) and Best (i.e., that yield the lowest cost) were the same. However, as also seen in Table 3.4, RS were different. It shows savings as a minor effect when using the same number of foldable containers. In the case of SEAPORT, α ratios of the Bound and Best were different. In this case, additional minor effects created an increase of α values for Best and reduced costs more than for the other. In our study, AII under SEAPORT required the most foldable containers to establish additional minor effects ($\alpha = 0.44$).

Table 3.5: α values of Bound and Best for different scenarios and policies

Policy	Scenario	Bound	Best
BASIC	ADI	0.40	0.40
	AII	0.40	0.40
	SII	0.22	0.22
SEAPORT	ADI	0.36	0.40
	AII	0.36	0.44
	SII	0.00	0.00

To understand the characteristics of effects caused by use of foldable containers, we conducted a sensitivity analysis. To calculate minimum total costs, α was adjusted to the optimal value in each case. The objective of the first sensitivity analysis was to check the relationship between effects for use of foldable containers and the total supply and demand. The total supply and demand of each customer were changed to certain ratios (1, 2, 3, 4, 50, 100). For example, ratio 3 means that demand and supply are tripled. The RS of the Bound and Best for different scenarios under different policies and with varying supply and demand ratios were calculated in Table 3.6.

Table 3.6: Relative Savings (%) of Bound and Best for different scenarios under different policies and with varying supply and demand ratios

Scenario	Supply & Demand ratio	BASIC		SEAPORT	
		Bound	Best	Bound	Best
ADI	1	41.56	43.66	31.19	34.17
	2	44.76	45.68	35.22	36.43
	3	44.46	45.58	35.05	36.33
	4	46.22	46.22	37.20	37.20
	50	46.08	46.20	37.10	37.17
	100	46.22	46.22	37.20	37.20
AII	1	44.43	45.85	42.90	43.95
	2	48.30	48.34	48.36	48.36
	3	48.73	48.73	48.31	48.31
	4	49.59	49.59	49.68	49.68
	50	49.54	49.54	49.63	49.63
	100	49.59	49.59	49.68	49.68
SII	1	17.10	17.10	0.00	0.00
	2	17.10	17.10	0.00	0.00
	3	17.10	17.10	0.00	0.00
	4	17.10	17.10	0.00	0.00
	50	17.10	17.10	0.00	0.00
	100	17.10	17.10	0.00	0.00

In general, RS increased when total supply and demand increased. The gaps between savings under both Bound and Best decreased when the total supply and demand increased. This finding can be explained by customers having opportunity to build folded packs without minor effects. In an interesting finding, increasing the total supply and demand did not always lead to increased savings. A certain number of additional containers are needed to build a folded pack, and the increase in total demand and supply does not always meet this threshold value for containers. For instance, in the case of Ratio 3 for ADI, savings decreased under both BASIC and SEAPORT, but in the case of SII, the impact of increasing total supply and demand was relatively small compared to other cases. Specifically, in the case of SII with BASIC, minor effects did not transpire. In the case of SII under SEAPORT, neither major nor minor effect transpired; therefore, savings were unaffected by the total demand and supply. Interestingly, the relative savings were much less than those for foldable containers which ideally reduced the repositioning costs. The reason was the trade-off between savings by folded packs and additional costs caused by folding and unfolding costs.

We also performed a sensitivity analysis based on the number of nodes. They were generated with the same way as the previous SDRP instances except the number of nodes. The results are shown in Table 3.7. Regardless of the changes in the number of nodes, the values of RS did not show distinctive trends. The flows of empty containers were disaggregated when the number of nodes is increased. It leads to the reduced number of building folded packs in each node. On the other hand, the value of α decreased as the number of nodes is increased.

Table 3.7: Relative savings (%) and the best α value for different nodes under different scenarios and policies

Number of nodes	ADI		AII		SII	
	RS	α	RS	α	RS	α
6	43.66	0.40	45.85	0.40	17.10	0.22
8	47.11	0.41	47.87	0.41	21.51	0.28
10	44.50	0.37	45.95	0.37	20.87	0.27
12	35.50	0.32	42.34	0.32	16.59	0.19

3.5 Conclusions

The main contribution of this chapter lies in the definition of the intrinsic major and minor effects of using foldable containers and the analysis of these effects under different scenarios and policies. The minor effect is more effective as the number of small deliveries increases. As the experimental results showed, the minor effect decreases as the number of containers increases. The degree of effect is higher in hinterland areas than in maritime areas. Because it is easier to change routes in hinterland areas than in maritime areas, a logistics company can change routes and achieve additional cost savings. This chapter highlights policy implications for governments, port construction companies, and logistics companies that intend to introduce foldable containers. Because the policies and scenarios we have considered address where to install the folding equipment or where to build the depot, various factors such as long-term investment costs should be considered by policymakers. The model we have developed will help decision-makers analyze the problem quantitatively.

Chapter 4

Effects of foldable containers in the dynamic situation of maritime transport

4.1 Introduction

The shipping and logistics market continues to grow, and international container volume is also increasing. The RWI/ISL (Leibniz Institute for Economic Research and the Institute for Shipping Economics and Logistics) container throughput index, a representative container volume index, has also increased, despite the COVID-19 pandemic, as shown in Figure 4.1. Also, the number of container ships continues to increase, as borne out in 2021 Statista Research Department [3] report, which claimed, "The number of container ships in the global fleet increased from 4,966 ships in 2011 to 5,371 ships in 2020".

However, despite this quantitative growth, shipping and maritime logistics are vulnerable to the disadvantages of slow speed and inflexibility. Such weaknesses have been revealed during the COVID-19 pandemic.

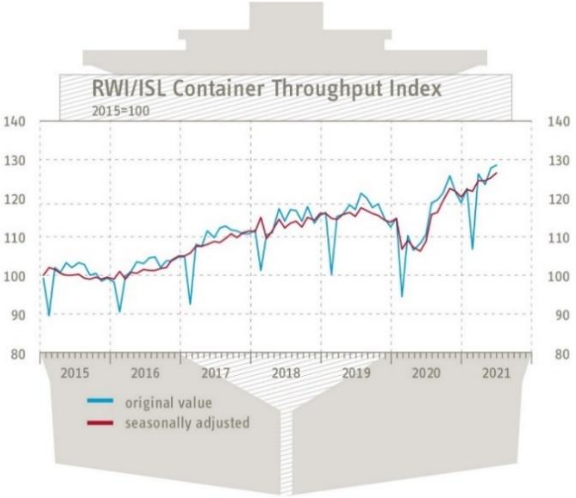


Figure 4.1: RWI/ISL container throughput index[4]

Although global trade volumes sharply declined in early 2020 because of widespread COVID-19, logistics demands rapidly recovered after the launch of the vaccination by the end of 2020. Moreover, because social and commerce-related transactions are changing from traditional face-to-face interactions and moving to remote interactions, people's consumption patterns are shifting, and the volume of global logistics is increasing. Unexpected demand increases have amplified the chronic imbalance in trade volumes between Asia and North America. In Asia, there was an unfavorable situation in which empty containers, including leased containers, were not available when needed. On the other hand, many surplus empty containers were left in North America while no ships were available to travel to Asia. The Shanghai Containerized Freight Index (SCFI), a representative index of container fares, continued to increase. The index started at 1022.72 in January 2020, rose to 2870.34 in January 2021, and finally reached 4810.98 in December 2021. In this way, the imbalance and shortage of container ships and containers are intensifying.

Various academic studies are being conducted to manage the uncertainty and fluctuation. Prior to COVID-19, studies mainly focused on the changing demand or port disruptions. Di Francesco et al.[21] solved the problem of repositioning empty containers by dividing the disruption of a given port into two disruptions and using multi-scenario optimization. Song and Dong[53] studied the container relocation and fleet size decision of customer demand in uncertain and imbalanced situations. Lee and Moon[37] studied robust optimization for variable demands by considering foldable containers. Tanaka et al.[55] researched demand fluctuation risk to formulate vessel assignment plans to account for inter-company competition. After COVID-19 occurred, Notteboom et al.[47] analyzed and compared the impact it had on the shipping logistics business to the 2008–2009 financial crisis, and Koyuncu et al.[34] predicted a decrease in container throughput by performing time series analysis using data from the past and from the early days of the COVID-19 pandemic.

In this chapter, we analyzed the effects of using foldable containers in dynamic situations, focusing especially on the container imbalance problem in maritime areas. As for the effect of foldable containers on the empty container repositioning network, Erdoğan and Kabadurmuş[25] compared impacts of foldable containers, street-turn, depot-direct strategies, and their combinations on empty container repositioning, and Kim et al.[30] showed, through mixed-integer programming(MIP), that the flow of empty container repositioning in the hinterlands changes with the introduction of foldable containers. Moreover, as for the additional restrictions due to foldable containers, Moon and Hong[41] researched the installation of the special equipment needed to operate foldable containers, and Kim et al.[30] analyzed additional loading rules and effects when considering the characteristics of foldable containers. Jeong et al.[27] studied the impact of determining optimal devanning times, which is an important consideration when using foldable containers. However, advanced studies did not address the fluctuation mitigation effects that arise from exploiting the beneficial characteristics of foldable containers. We summarize the relevant literature in Table 4.1.

Table 4.1: Comparisons of recent papers related to this research

Authors (year)	Considering Foldable Container	Changing Situation	Concepts
Konings and Thijs[33]	√		Introduce foldable containers to academia
Konings[32]	√		Basic advantages and disadvantages of foldable containers which related to space saving
Dong and Song[24]		Demand	Fleet sizing and empty container repositioning problem in multiple vessels and ports
Shintani[50]	√		Analysis of the effect of the foldable container according to the fleet size
Di Francesco et al.[21]		Shutdown	Repositioning of empty containers with port disruptions using single and multiple scenarios
Moon and Hong[41]	√		Installation of foldable container equipment and minimization of total repositioning cost
Wang et al.[58]	√		Ship type decision in liner shipping considering foldable containers
Erdoğan and Kabadurmuş[25]	√		Analysis of foldable containers, street-turn, and depot-direct strategies effects on empty container repositioning
Jeong et al.[27]	√		Determining the optimal devanning time according to the scenario in the container supply chain
Kim et al.[30]	√		Analysis of rules and cost distribution issues that arise when introducing foldable containers
Lee and Moon[37]	√	Demand	Propose robust formulation for the empty container repositioning problem which

			considers foldable containers
Tanaka et al.[55]		Demand	Formulating vessel assignment plans
Kim et al.[31]	√		Analysis of hinterland network changes when considering foldable containers
Koyuncu et al.[34]			Predicts the volume of containers after COVID-19 by using the SARIMA model
Notteboom et al.[47]		Throughout the shipping industry	Analysis of shipping industry disruptions after COVID-19 crisis by comparing it to the 2008-2009 financial crisis
This dissertation (Chapter 4)	√	Shutdown, demand, fleet size	Analysis of using foldable containers effectively under dynamic situation

Foldable containers would be significantly effective for several dynamic situations in reducing transportation and storage costs. Because foldable containers can be folded or unfolded depending on the situation, they can swiftly respond to restrictions and fluctuations. This can act as a buffer for some dynamic situations. Therefore, we experimented with the effect of foldable containers in various dynamic situations: shutdowns, demand fluctuations, fleet size fluctuations, and combinations of each situation, respectively. We described the problem in Section 4.2 and explained the mathematical model in Section 4.3. Section 4.4 shows the computational results, and Section 4.5 concludes and provides managerial insights.

4.2 Problem description

In this chapter, we want to analyze the effect of foldable containers in trading situation changes. Because many different dynamic situations can occur, we would like to analyze when foldable containers are effective and how many foldable containers are needed in each case. We assume only two ports to simplify. Each port trades with the other, initially balancing exports and imports. Each port may have the same export and import volumes (ideal case), or it may be different as seen in the real world. We want to identify the problems in case of a shutdown situation, demand fluctuation, or fleet size fluctuation. We believe this is especially timely research. This is because many shutdowns occur these days, such as uncertain port closures and regular inspections. In addition, the lack of containers and container vessels continues to be a problem. We studied how these problems disappear when foldable containers are used. Assumptions in this chapter are as follows:

(1) Only two mutually trading ports exist and the total number of containers is fixed.

(2) The setup considers returned containers from customers on land, but does not consider backhauling.

(3) Unsatisfied demand is considered as a backorder situation, and leases are not considered.

(4) Only reduction costs, sea transportation costs, inventory costs, and backorder costs are considered.

(5) Space limitations of container vessels are considered, but space limitations of warehouses are not considered.

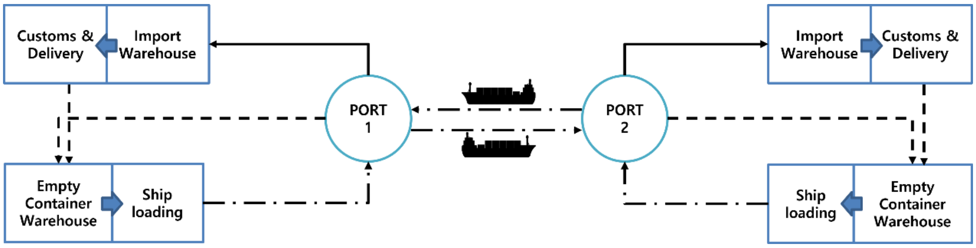


Figure 4.2: Network flow of container(full container: solid line, empty container: dotted line)

The network flow that reflects the above assumptions is shown in Figure 4.2. Export and import processes are carried out at each port. Vessels are carrying full and empty containers between two ports. Because vessels have capacity limitations, the fluctuation of the vessels' capacities is expressed through the capacity of the given vessel's changes over time. When containers arrive at each port, full containers move to the import warehouse and go through customs clearance. If a shutdown occurs, the customs process will be suspended. Containers in an empty state after being delivered to the customer will be moved back to the empty container warehouse. On the other hand, imported empty containers are moved directly to the empty container warehouse. If products are exported from each port, the empty container will be matched and transported to another port. If there are too many exported products and they cannot be matched with empty containers, then a backorder situation occurs, and it has to be resolved in the subsequent periods.

4.3 Mathematical model

We developed a mathematical model to solve the shutdown problem. The sets, indices, parameters, and variables are listed in Table 4.2.

Table 4.2: Sets, indices, parameters, and decision variables

Set and indices	
$\boldsymbol{P}$	set of ports
$\boldsymbol{T}$	indices of time periods
$\boldsymbol{C}$	types of containers
$\boldsymbol{R}$	possible port-to-port routes
Parameters	
$\boldsymbol{V_{ij}^{t}}$	capacity of the vessel in period t, route (i,j)
$\boldsymbol{D_{ij}^{t}}$	demand route (i,j) in period t
$\boldsymbol{IT_{i}}$	import processing time in port i
$\boldsymbol{LT_{i}}$	onshore processing time in port i
$\boldsymbol{ET_{i}}$	export processing time in port i
$\boldsymbol{ST_{ij}}$	voyage time in route (i,j)
$\boldsymbol{SC_{ij}}$	voyage cost in route (i,j)
$\boldsymbol{SP_{ij}}$	voyage price in route (i,j)
$\boldsymbol{W_{i}^{t}}$	import process capacity in port i, period t
$\boldsymbol{IC_{i}}$	storage cost in port i
$\boldsymbol{BC_{ij}}$	backorder cost in route (i,j)
$\boldsymbol{FC_{i}}$	folding/unfolding cost in port i
$\boldsymbol{CF}$	holding cost of foldable container

$\boldsymbol{CS}$	holding cost of standard container
$\boldsymbol{NF}$	number of total holding foldable containers
$\boldsymbol{NS}$	number of total holding standard containers

Decision Variables

$\boldsymbol{x_{ijt}^{c}}$	number of container type c transported from port i to port j in period t
$\boldsymbol{im_{it}^{c}}$	number of container type c transported from port i to warehouse in period t
$\boldsymbol{l_{it}^{c}}$	number of container type c transported from port i to onshore process in period t
$\boldsymbol{e_{it}^{c}}$	number of container type c transported from empty container warehouse to port i in period t
$\boldsymbol{iw_{it}^{c}}$	number of container type c in import container warehouse at port i in period t
$\boldsymbol{ew_{it}^{c}}$	number of container type c in empty container warehouse at port i in period t
$\boldsymbol{b_{it}}$	number of backorders at port i in period t
$\boldsymbol{f_{it}^{c}}$	number of folding processes at port i in period t
$\boldsymbol{uf_{it}^{c}}$	number of unfolding processes at port i in period t

The constraints and objective functions are as follows:

$$\text{maximize} \quad \begin{aligned} &\sum_{(i,j)\in R}\sum_{t\in T} SP_{ij}(x_{ijt}^{1}+x_{ijt}^{3}) - \sum_{(i,j)\in R}\sum_{t\in T} SC_{ij}(x_{ijt}^{1}+x_{ijt}^{2}+x_{ijt}^{3}+x_{ijt}^{4}+\frac{1}{4}x_{ijt}^{5}) \\ &\quad - \sum_{(i,j)\in P}\sum_{t\in T} IC_{ij}(iw_{ijt}^{1}+iw_{ijt}^{3}+ew_{ijt}^{3}+ew_{ijt}^{4}+\frac{1}{4}ew_{ijt}^{5}) \\ &\quad - \sum_{t\in T}(CF\times NF+CS\times NS) - \sum_{(i,j)\in R}\sum_{t\in T} BC_{ij}\times b_{ijt} \\ &\quad - \sum_{i\in P}\sum_{t\in T} FC_{i}(f_{it}+uf_{it}) \end{aligned} \tag{4.1}$$

subject to

$$\begin{aligned} NS = {} & \sum_{(i,j)\in R} \sum_{s=t-ST_{ij}+1\ |s>0}^{t} (x_{ijs}^{1}+x_{ijs}^{2}) \\ & + \sum_{i\in P} \sum_{s=t-IT_{ij}+1\ |s>0}^{t} (im_{is}^{1}+im_{is}^{2}) \\ & + \sum_{i\in P} \sum_{s=t-LT_{ij}+1\ |s>0}^{t} (l_{is}^{1}+l_{is}^{2}) \\ & + \sum_{i\in P} \sum_{s=t-ET_{ij}+1\ |s>0}^{t} (e_{is}^{1}+e_{is}^{2}) \\ & + \sum_{i\in P} (iw_{it}^{1}+iw_{it}^{2}) + \sum_{i\in P} (ew_{it}^{1}+ew_{it}^{2}) \quad \forall t\in T \end{aligned} \tag{4.2}$$

$$\begin{aligned} NF = {} & \sum_{(i,j)\in R} \sum_{s=t-ST_{ij}+1\ |s>0}^{t} (x_{ijs}^{3}+x_{ijs}^{4}+x_{ijs}^{5}) \\ & + \sum_{i\in P} \sum_{s=t-IT_{ij}+1\ |s>0}^{t} (im_{is}^{3}+im_{is}^{4}+im_{is}^{5}) \\ & + \sum_{i\in P} \sum_{s=t-LT_{ij}+1\ |s>0}^{t} (l_{is}^{3}+l_{is}^{4}+l_{is}^{5}) \\ & + \sum_{i\in P} \sum_{s=t-ET_{ij}+1\ |s>0}^{t} (e_{is}^{3}+e_{is}^{4}+e_{is}^{5}) \\ & + \sum_{i\in P} (iw_{it}^{3}+iw_{it}^{4}+iw_{it}^{5}) \\ & + \sum_{i\in P} (ew_{it}^{3}+ew_{it}^{4}+ew_{it}^{5}) \quad \forall t\in T \end{aligned} \tag{4.3}$$

$$\sum_{i\in P} x_{ij(t-ST_{ij})}^{c} = im_{jt}^{c} \quad \forall\, j\in P, t\in T, c\in C \tag{4.4}$$

$$im_{i(t-IT_i)}^{c} + iw_{i(t-1)}^{c} = iw_{it}^{c} + l_{it}^{c} \quad \forall\, i\in P, t\in T, c\in\{1{,}3\}, t>IT_i \tag{4.5}$$

$$l_{it}^{1} + l_{it}^{3} \le W_{i}^{t-1} \quad \forall\, i\in P, t\in T, t>1 \tag{4.6}$$

$$l_{i(t-LT_i)}^{1} + im_{i(t-IT_i)}^{2} + ew_{i(t-1)}^{2} = ew_{it}^{2} + e_{it}^{1} + e_{it}^{2} \quad \forall\, i\in P, t\in T, t > IT_i, t>LT_i \tag{4.7}$$

$$l_{i(t-LT_i)}^{3} + im_{i(t-IT_i)}^{4} + ew_{i(t-1)}^{4} + uf_{i(t-1)} - f_{i(t-1)} = ew_{it}^{4} + e_{it}^{3} + e_{it}^{4} \quad \forall\, i \in P, t\in T, t>IT_i, t>LT_i \tag{4.8}$$

$$im_{i(t-IT_i)}^{5} + ew_{i(t-1)}^{5} - uf_{i(t-1)} + f_{i(t-1)} = ew_{it}^{5} + e_{it}^{5} \quad \forall\, i\in P, t\in T, t > IT_i \tag{4.9}$$

$$e_{i(t-ET_i)}^{c} = \sum_{j\in P} x_{ijt}^{c} \quad \forall\, i\in P, c\in C, t\in T, t>ET_i \tag{4.10}$$

$$x_{ijt}^{1} + x_{ijt}^{3} \le D_{ij}^{t} \quad \forall\, (i,j)\in R, t\in T \tag{4.11}$$

$$b_{ijt} = b_{ijt-1} + D_{ij}^{t} - x_{ijt}^{1} - x_{ijt}^{3} \quad \forall\, (i,j)\in R, t\in T, t>1 \tag{4.12}$$

$$x_{ijt}^{1} + x_{ijt}^{2} + x_{ijt}^{3} + x_{ijt}^{4} + {}^{1}\!/_{4}\, x_{ijt}^{5} \le V_{ij}^{t} \quad \forall\, (i,j)\in R, t\in T \tag{4.13}$$

$$x_{ijt}^{c} = 0 \quad \forall\,(i,j) \notin R, c \in C, t \in T \tag{4.14}$$

$$l_{it}^{2} = l_{it}^{4} = l_{it}^{5} = ew_{it}^{1} = ew_{it}^{3} = iw_{it}^{2} = iw_{it}^{4} = iw_{it}^{5} = 0 \quad \forall\, i \in P, t \in T \tag{4.15}$$

$$x_{ijt}^{c}, \in Z_{+} \ \forall\,(i,j) \in R, c \in C, t \in T \tag{4.16}$$

$$im_{it}^{c}, l_{it}^{c}, e_{it}^{c}, iw_{it}^{c}, ew_{it}^{c}, b_{it}^{c}, f_{it}^{c}, uf_{it}^{c} \in Z_{+} \ \forall\, i \in P, c \in C, t \in T \tag{4.17}$$

$$1/_{4}\, x_{ijt}^{5} \ \in Z_{+} \ \forall\,(i,j) \in R, c \in C, t \in T \tag{4.18}$$

$$1/_{4}\, e_{it}^{5}, 1/_{4}\, ew_{it}^{5}, 1/_{4}\, im_{it}^{5} \ \in Z_{+} \ \forall\, i \in P, t \in T \tag{4.19}$$

The objective function (4.1) maximizes the total profits based on the revenue obtained from transporting freight, deducting container transportation cost(including empty repositioning), storage cost, container holding cost, backorder cost, folding cost, and unfolding cost. Constraints (4.2) and (4.3) explain that the number of containers of each type is fixed at each period. Constraint (4.4) is the balance equation of import containers, and constraint (4.5) is the balance equation of import warehouses for full containers. Constraint (4.6) expresses processing capacity at customs. Constraints (4.7), (4.8), and (4.9) are the balance equation of empty container warehouses, and constraint (4.10) is the balance equation of export containers. Constraints (4.11), (4.12), and (4.13) are demand constraints, backorder, and vessel capacity constraints, respectively. Constraints (4.14) and (4.15) are on non-movable paths. Constraints (4.16) and (4.17) shows that variables are integer, and constraints (4.18) and (4.19) express that foldable packs have to be a multiple of four.

4.4 Computational experiments

4.4.1 Overview

We analyzed the effect of using foldable containers when dynamic situations occurred in a given network flow. Total considered periods were set to 13 weeks. Voyage time between the ports was assigned to 2 weeks. The time required for the import process, onshore process, and export process at each port was set to 1 week each. We analyzed 10 different situations, which included shutdowns, demand fluctuations, fleet size fluctuations, and a combination of each case. The shutdown was expressed as a situation in which the port closed once every 4 weeks, and the import process was stopped. When the fleet size and demand fluctuations occur together, this, by design, increases (or decreases) the vessels' capacity, which arises after demand increases (or decreases), thereby reflecting that demand is a leading indicator of the vessels' capacity. We also consider whether imports and exports were balanced at each port, the number of containers used, and the percentage of foldable containers. Through these experiments, we want to determine if foldable containers are effective and how many foldable containers will be needed when we are aware of various dynamic situations. In addition, we also considered which of the multiple situations given affects the need for foldable containers.

Experiments were conducted on 9,020 situations and included the following inputs described in Table 4.3. The cost data used in the experiments are shown in Table 4.4. The models were implemented using XPRESS-IVE 8.6 with the Xpress-MP mathematical programming solver. Experiments were conducted with an Intel® Core™ i5-37400 CPU 3.0 GHz with 8.0 GB of RAM in Windows 10.

Table 4.3 The types of situations that are considered

Import and export balances (2 cases)	- balanced: 100 FEU (port 1→port 2), 100 FEU (port 2→port 1) per week - imbalanced: 60 FEU (port 1→port 2), 100 FEU (port 2→port 1) per week
Dynamic situations (10 cases)	1. normal 2. shutdown 3. fleet size decrease and increase 4. fleet size increase and decrease 5. demand decrease and increase 6. demand increase and decrease 7. fleet size & demand decrease and increase 8. fleet size & demand increase and decrease 9. shutdown, fleet size & demand decrease and increase 10. shutdown, fleet size & demand increase and decrease
Number of containers (41 cases)	800~1600 (balanced case), 640~1440 (imbalanced case), gap: 20
Container ratio (foldable : standard; 11 cases)	0~1 (gap: 0.1)

Table 4.4: Cost data (per week, FEU)

	Port 1	Port 2
Voyage prices / costs	\$250 / \$100 (to Port 2)	\$300 / \$100 (to Port 1)
Backorder costs	\$125 (to Port 2)	\$150 (to Port 1)
Storage costs	\$1.2	\$1
Folding/unfolding costs	\$15	\$10
Container holding costs	\$2 (standard), \$3 (foldable)	

4.4.2 Experiment results

There were 41 cases related to the number of containers, but they were too many to be expressed in figures. Therefore, we chose two cases as graphs to analyze the shape. A sampling of 900 and 1,100 containers was selected in a balanced situation, and a sampling of 740 and 940 containers was selected in an unbalanced situation, which is shown in Figures 4.3, 4.4, 4.5, and 4.6, respectively. The horizontal axis is the ratio of the standard container and foldable container, and the vertical axis is the total profit attained.

In Figures 4.3 and 4.4, experiments showed that foldable containers have no effect and only reduce profit in many balanced cases, in which the container ratio is 1 (using only standard containers). Because standard containers are sufficient to handle each situation, an increase in the percentage of foldable containers only increases operating costs. However, in Figures 4.5 and 4.6, foldable containers were meaningful in many cases when in an unbalanced situation. This circumstance was so because foldable containers are transported faster to areas with a shortage when many empty containers are left on one side.

We found a peak point when a foldable container shows the best effect in some cases because there is a trade-off to reducing shortages and increasing operating costs in the use of foldable containers. We summarized the peak points in each case in Tables 4.5 and 4.6. In a balanced situation, foldable containers had limited effects. Even if several dynamic situations occur, seldom is there a shortage of containers. Foldable containers were effective only in cases 2, 8, and 10, when the shutdown occurred, or when the demand and fleet size were increased first and decreased after. Otherwise, in the unbalanced situation, foldable containers were required in all cases.

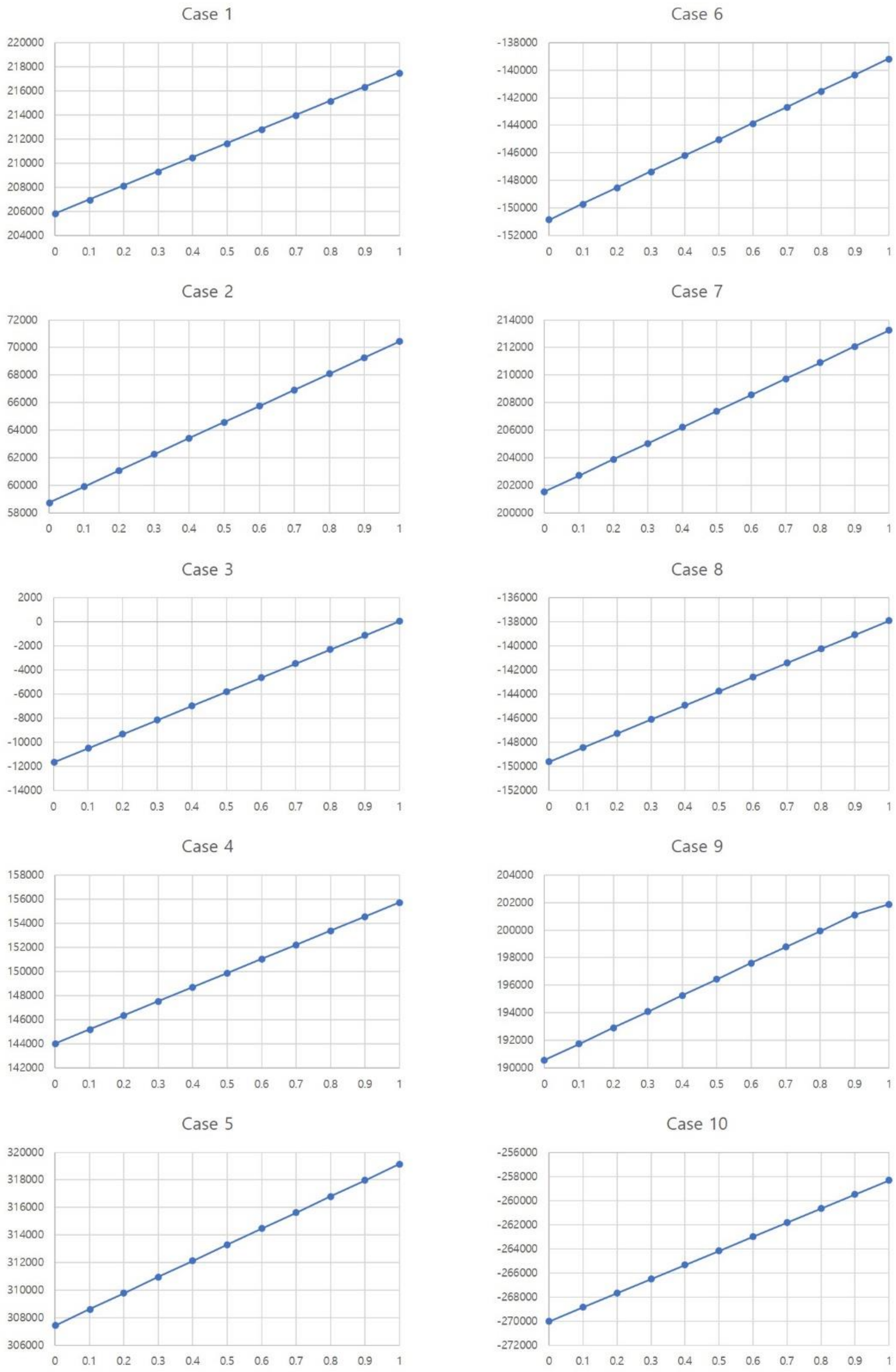
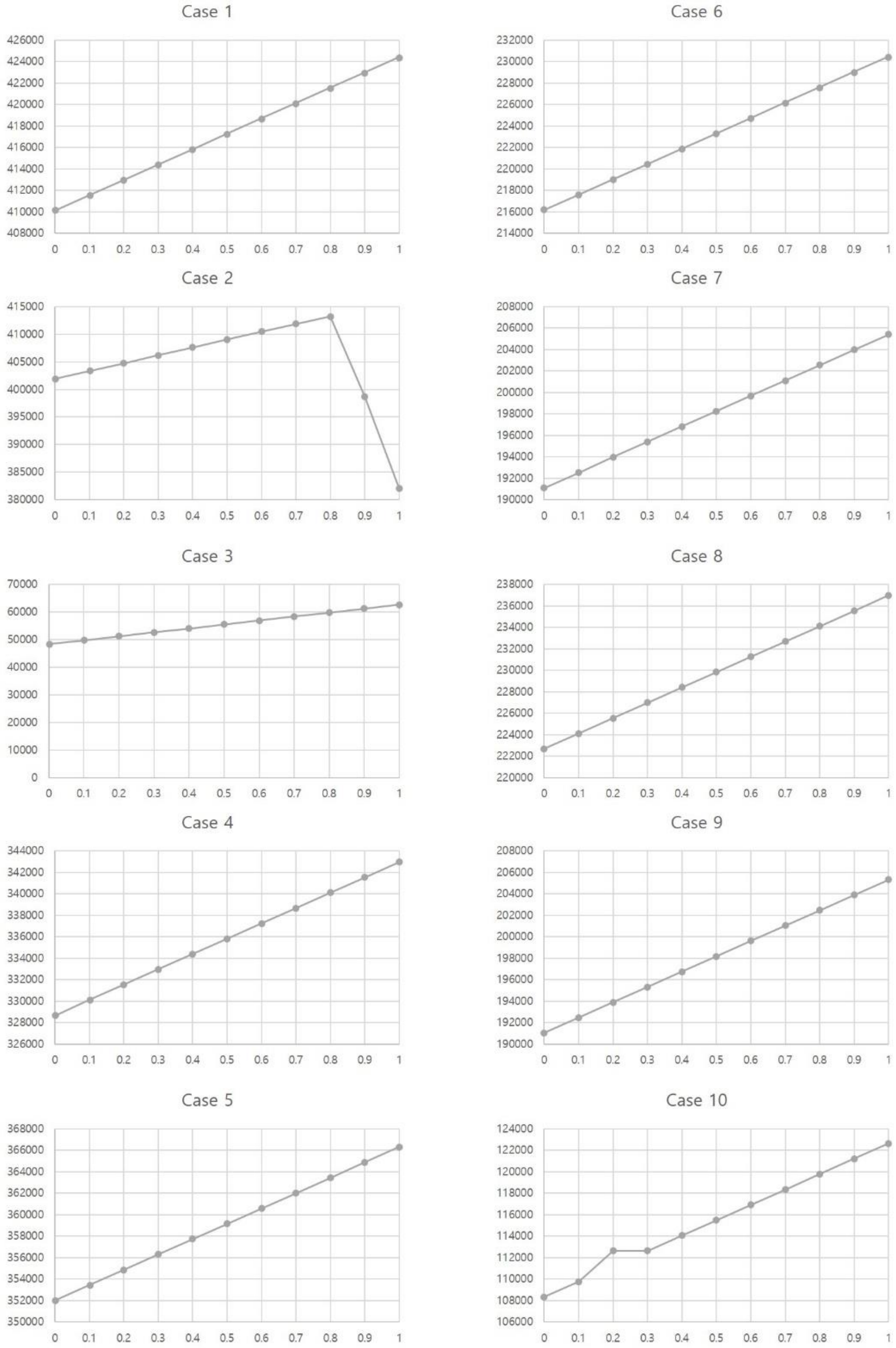


Figure 4.3: 900 containers in case of balanced situation



Case 1

Case 6

Case 2

Case 7

Case 3

Case 8

Case 4

Case 9

Case 5

Case 10

Figure 4.4: 1100 containers in case of balanced situation

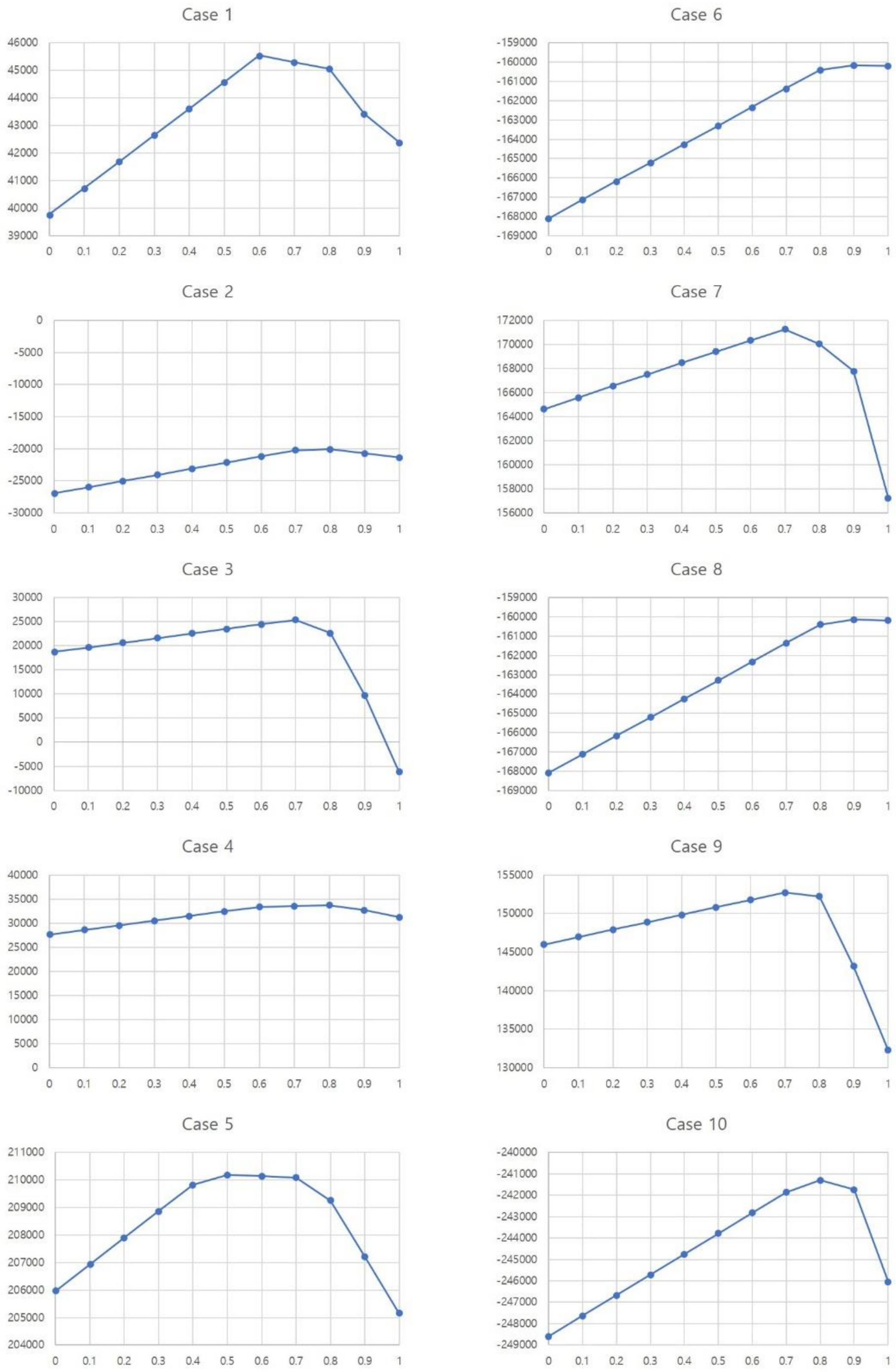


Figure 4.5: 740 containers in case of unbalanced situation

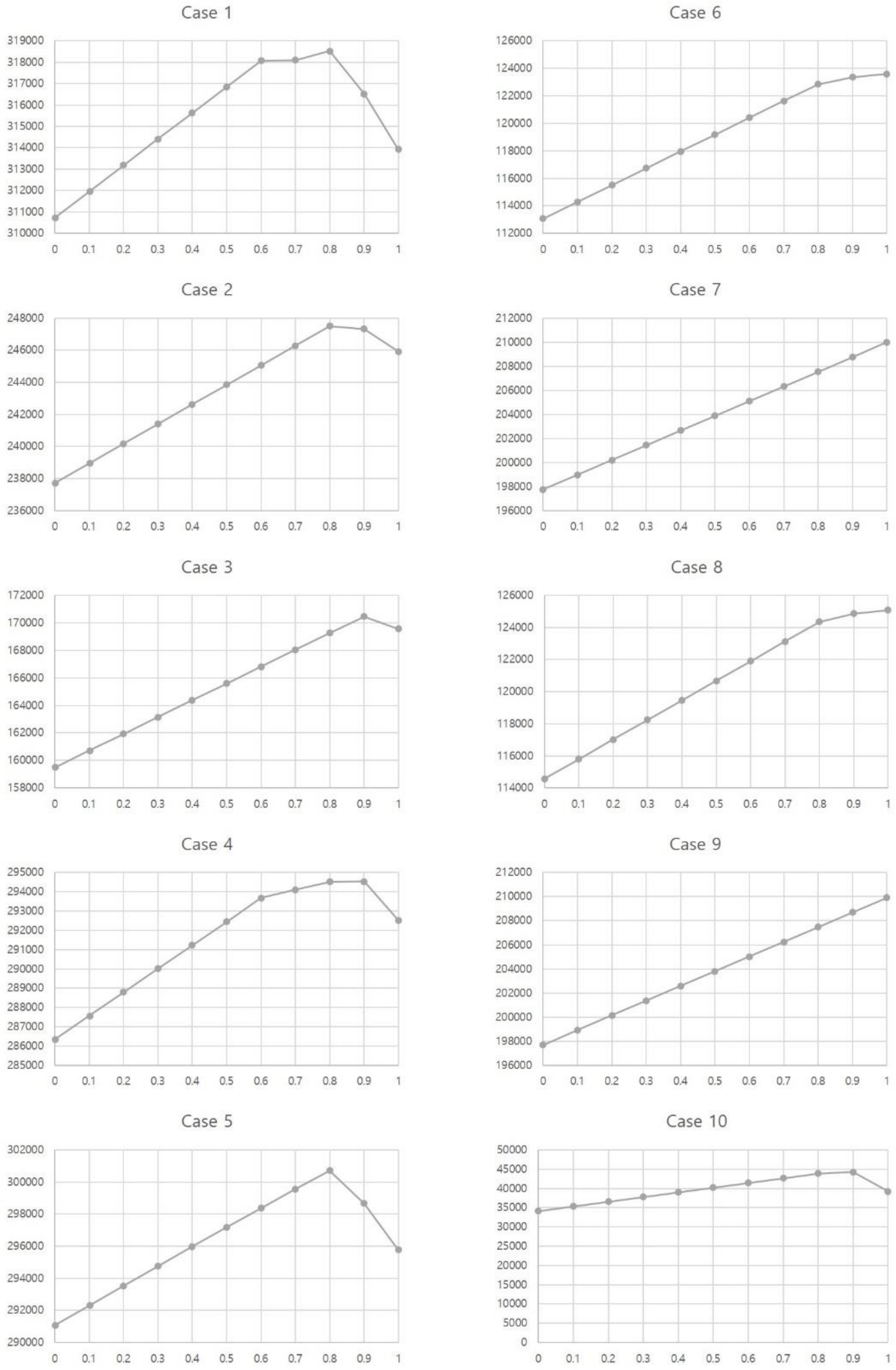


Figure 4.6: 940 containers in case of unbalanced situation

Foldable containers were introduced to solve the imbalance of containers quickly. Therefore, we can check that the foldable container is effective even in case 1, which is not a dynamic case. When dynamic situations were considered, more complex effects have occurred. First, fewer foldable containers are required in a shutdown (case 2) than normal case(case 1) in an unbalanced situation. Because backorders occur on account of shutdowns, the use of folded foldable containers decreases as containers are sent to full containers rather than empty containers. In cases of fleet size fluctuations, the standard containers can be relocated in advance when there is plenty of space, so fewer foldable containers are required. On the other hand, in cases of demand fluctuations, more foldable containers were required for a demand increase after a decrease, but fewer foldable containers were required for the demand decrease after the increase. This is because when demand decreases and increases, the container could be relocated in advance because of the capacity of the vessel. However, when demand increases and decreases, the number of backorders increases, and folded containers cannot be sent from the import port. Thus, the container cannot be folded, and the advantages of foldable containers cannot be utilized.

In our experiment, similar to reality, we assumed that surplus containers were stored in an export port. Though if there were surplus containers in the import port, we can estimate those foldable containers would be effective. We conducted additional experiments on this case and found that foldable containers were sufficiently effective. Experiments concluded that the effect of foldable containers varies depending on shutdown, demand and fleet size fluctuations, and the number of containers. We found that when a backorder exists in one port and many containers remain in the other port at the same time, the effect of the foldable container is excellent. In many cases, foldable containers were also effective when the total number of containers was insufficient. On the other hand, only standard containers alone were enough if the number of containers was sufficient.

Through this experiment, the case in which the effect of the foldable container was clearly shown was an unbalanced situation and shutdown occurred. Moreover, the appropriate ratio of foldable containers also depends on the total number of containers. As a result, we can summarize that foldable containers can reduce costs when various dynamic situations are given. Because trade-off exists, optimal numbers of foldable containers are different for each situation.

Table 4.5: Peak points in a balanced situation (horizontal: number of containers, vertical: cases)

	800	820	840	860	880	900	920	940	960	980	1000	1020	1040	1060	1080	1100	1120	1140	1160	1180
case1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case2	1	1	1	1	1	1	1	1	1	1	1	1	0.9	0.8	0.8	0.8	0.8	0.8	0.9	1
case3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.9	1	1

	1200	1220	1240	1260	1280	1300	1320	1340	1360	1380	1400	1420	1440	1460	1480	1500	1520	1540	1560	1580	1600
case1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case8	0.9	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case10	0.9	0.9	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1	1	1	1	1

Table 4.6: Peak points in an imbalanced situation (horizontal: number of containers, vertical: cases)

	640	660	680	700	720	740	760	780	800	820	840	860	880	900	920	940	960	980	1000	1020
case1	0.8	0.8	0.8	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8
case2	1	1	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9
case3	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1
case4	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9
case5	0.8	0.7	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.7	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9
case6	1	1	1	1	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1
case7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1	1	1
case8	1	1	1	1	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1
case9	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1	1	1
case10	1	1	1	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

	1040	1060	1080	1100	1120	1140	1160	1180	1200	1220	1240	1260	1280	1300	1320	1340	1360	1380	1400	1420	1440
case1	0.9	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case2	0.9	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case4	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case5	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
case10	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

4.5 Conclusions

In this chapter, we observed that foldable containers are effective in dynamic situations. This is because foldable containers act as buffers, which resolve situations of container imbalance faster. In particular, using foldable containers was more effective when exports and imports were not proportionate. This result suggests that the application of foldable containers in the real world, such as when container imbalances occur between the United States and China, can effectively solve the imbalance problem. However, the experiment showed that the most effective proportion of foldable containers varies depending on the situation.

The number of most efficient foldable containers differed from case to case. For each case, the number of optimal foldable containers required was different. If foldable containers were more than the required quantity, the cost would increase. Therefore, each shipping company may be reluctant to introduce foldable containers because effective situations are limited and can change.

We suggest implementing a leasing system to overcome the limitations of foldable containers. If a lease of foldable containers were to be implemented, in which available containers could act as buffers, it would be possible to resolve the container imbalance issue more effectively than the current leasing setup of standard containers allows for. Therefore, for each shipping company, *a short-term foldable container lease strategy* can be devised to benefit from the effectiveness of using foldable containers in dynamic or uncertain situations such as COVID-19. Each shipping company tries to predict various dynamic situations to calculate the optimal lease quantity. With robust predictions and appropriate foldable container leases, shipping companies will be able to pursue more significant incomes.

Moreover, the manufacturing companies of foldable containers should install publicly accessible equipment and repair facilities at each port to promote the lease market of foldable containers. The leasing companies can effectively address the different demands from shipping companies by centralizing foldable containers and getting more significant benefits than they currently do through the leasing of standard containers. On the government side, there are presently many policies in place in each country to address the container imbalance, which could be rectified by implementing foldable containers and introducing them to leasing possibilities.

We hope that multiple players can effectively overcome various dynamic situations and develop shipping and logistics by using foldable containers through this chapter.

Chapter 5

Conclusion and future research

Containers have led the development of the shipping industry and logistics sector and have significantly contributed to enriching human life. Various methods have been developed to make this containerization more effective, and we have noted foldable containers among them. Foldable containers are just being commercialized in the hope that their potentials for further advancement could be beyond our imagination. We also studied the additional conditions and effects that could occur among the various application methods.

In Chapter 2, we proposed top-stowing rule that arises when foldable containers are introduced and developed the MIP model that can minimize crane operation from a global perspective. In addition, we developed an effective heuristic to reduce calculation time, and a cost-sharing method was recommended to solve the problem of cost distribution that may arise between ports. Future research includes three 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 to deal with larger instances. Though the MIP model is effective from the global optimal perspective, it requires an increase in computation times when foldable containers are taken into account. The 2-port method is able to reduce computation times significantly, but the efficiency performance varies depending on the dataset. Therefore, heuristics under the global optimal perspective are highly recommended to obtain heuristic solutions 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 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 chapter 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. In addition, if the technology of foldable containers ultimately develops and becomes strong enough, the top-stowing rule may not be required. It would also be meaningful to compare the repair cost of foldable containers and the operation cost of additional crane operations according to the top-stowing rule.

In Chapter 3, we analyzed the effect of foldable containers on the hinterland that was not generally considered. A single port and multiple port mathematical model were developed to analyze the new effects of foldable containers, minor effects. In particular, for single ports, various scenarios and policies were analyzed through computational experiments. However, a larger-size problem, such as one with a greater number of nodes, was not considered. In addition, we did not consider inventory policies, which can be influenced by the use of foldable containers. Accordingly, for future research, we will include inventory and backlog costs in the model and expand the planning horizon into multiple periods. Different types of foldable containers are still being developed and are competing to become a new standard. This study can be used to analyze the value of foldable containers in hinterland areas and help governments establish relevant legislation and policies.

Finally, we analyzed the effect of foldable containers on the increasingly deepening dynamic situations in Chapter 4. We developed the MIP model that can analyze the effectiveness of foldable containers under various dynamic situations such as shutdown, demand fluctuations, and fleet size fluctuations. We used the developed model to derive results to find situations in which foldable containers are effective. We think that the use of foldable containers are especially effective in imbalance and shutdown situations. Therefore, we will study different shutdown and imbalance situations for future research. Quantitative analysis is needed because the required quantity of foldable containers is expected to change depending on the frequency and predictability of shutdowns or imbalance levels.

Moreover, when foldable container leases are introduced, numerous studies on behavior from the perspective of multiple players can be conducted. In particular, additional policies can be considered from the perspective of the governments, leasing companies, and shipping companies. We expected that each player's modeling and simulation of decisions could be meaningful. Overall, because we analyzed the problem based on the MIP model, there is a limitation to responding when the situation continues to change. Exploring fluctuating global optimal solutions in statistically changing conditions will also be an interesting topic.

We studied the new effects of foldable containers through this dissertation. Because foldable containers are still in the early stage of commercialization, there is a lack of information on failure rates, repair costs, operating costs, purchase costs, etc. However, we found that foldable containers are effective at the current technology level through this study. With the development of foldable container technology, foldable container's utility will increase. We expect that academia and industry experts would effectively utilize new technologies, foldable containers.

Various new types of containers are still developing nowadays. Innovations in logistics networks are expected by developing and researching foldable containers and various innovative containers.

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국문초록

컨테이너 화 이후로 해상 물류는 폭발적으로 증가하였고 세계화와 산업 발전을 선도하였다. 하지만 무역량의 증가와 비례하여 수출입 불균형으로 인한 컨테이너의 불균형 문제도 심화되었다. 이러한 문제를 해결하기 위해 다양한 연구자들의 노력이 있었고, 그 중 접이식 컨테이너라는 새로운 개념의 컨테이너가 개발되었다. 하지만 아직 접이식 컨테이너는 상용화 초기 단계이며, 이를 활용한 여러 효과에 대한 연구는 부족한 실정이다.

본 논문에서는 접이식 컨테이너가 도입되었을 때 미칠 수 있는 영향과 그 효과에 대해 다루었다. 먼저 접이식 컨테이너가 크레인 활동에 미치는 영향을 분석하고, 전역적 관점으로 크레인 활동을 줄일 수 있는 방법에 대해 분석하였다. 두 번째로 육상에서의 접이식 컨테이너 적용이 해상과는 다르다는 점에 주목하여 그 효과를 분석하였다. 마지막으로 2008 금융위기와 COVID-19 이후에 증가하고 있는 해운물류의 각종 변동하는 상황 하에서의 접이식 컨테이너 효과에 대해 새로운 통찰을 제공하였다.

1장에서는 간단하게 컨테이너화와 접이식 컨테이너에 대해 설명하고 문제를 주목하게 된 이유와 그 성과를 서술하였다. 2장에서는 접이식 컨테이너가 도입됨에 따라 생길 수 있는 ‘상단 적재 규칙’이 적용되었을 때의 크레인 활동의 변화를 살펴보고 전역적 최적화가 지역적 최적화보다 효과적임을 보였다. 더불어 전역적

최적화를 도입하였을 때 직면할 수 있는 비용 분배 문제에 대해서도 조망하여 그 해결책을 제시하였다. 3장에서는 육상에서 접이식 컨테이너가 수송공간을 줄여주는 장점 외에 경로를 바꾸는 효과가 존재함을 보이고, 다양한 시나리오와 정책에 따라 그 효과가 어떻게 변화하는지에 대해 분석하였다. 4장에서는 증가하는 다양한 변동상황 각각에 대해 접이식 컨테이너의 효과에 대해 분석하였다. 이를 토대로 각 상황에 맞는 최적 접이식 컨테이너 개수를 도출하고 임대 정책을 통해 대응할 수 있다는 통찰을 도출하였다. 5장에서는 본 논문의 결론과 향후 연구 방안에 대해 서술하였다.

본 논문에서 제안하는 문제와 그 해결 방법은 학술적 및 산업적으로 의미가 있다. 학계에는 실제 존재하는 현장의 문제들을 제시하고 문제를 효과적으로 해결할 수 있는 방법들을 제안한다. 산업계에는 신기술인 접이식 컨테이너의 도입에 따라 발생할 수 있는 문제에 대해 정량화 및 모형화를 통한 해결방법을 제시한다. 본 논문을 통해 산업의 발전과 학문의 발전이 함께 이루어질 수 있을 것으로 기대한다.

주요어: 접이식 컨테이너, 컨테이너 불균형, 컨테이너 적재, 육상 컨테이너 수송, 변동 상황, 공급망 관리

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