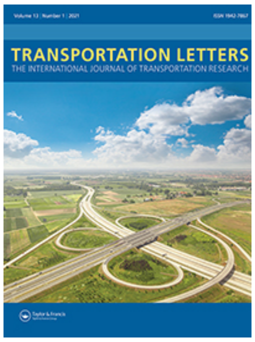

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Transportation Letters

The International Journal of Transportation Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ytrl20

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TRANSPORTATION LETTERS
2021, VOL. 13, NO. 1, 53–63
https://doi.org/10.1080/19427867.2019.1702249

Effects of using foldable containers in hinterland areas

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ABSTRACT

Hinterland transportation costs constitute a significant portion of total container transport costs. However, the repositioning effects of empty containers in hinterland areas have not been studied well compared to those in maritime areas. In addition, the effects of using foldable containers have not been investigated fully at an operational level. In this study, we analyze the effects of using a restricted number of foldable containers in hinterland areas. Mathematical models were developed to minimize total costs, and various effects of using foldable containers were investigated. To evaluate the real-world situation with the models, different customer scenarios and port policies were considered. The experiment results showed that foldable containers could notably reduce total costs. They also indicated that each effect could vary significantly depending on conditions. Therefore, the trade-offs between cost savings and additional costs incurred by using foldable containers should be contemplated in order to exploit foldable containers successfully in hinterland areas.

KEYWORDS

Hinterland transportation; integer programming; foldable container; empty container; container transport; container fleet management

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 the world trade volume involves container shipping (Di Francesco, Lai, and Zuddas 2013). Therefore, research has been widely conducted for effective ocean shipping, and a recent review was offered by Wang and Meng (2017). However, container shipment has drawbacks created by imbalanced trades across regions (Theofanis and Boile 2009). 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, oversupply or undersupply of empty containers are among the main issues in the container shipping industry (Song and Dong 2015). 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 (1993) was published. Shintani et al. (2007) introduced a network design for liner shipping. Song and Carter (2009) analyzed critical factors affecting empty container repositioning. Dong and Song (2009) 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 (2012) combined the empty container-repositioning problem with a cargo routing problem. Moon, Ngoc, and Hur (2010) looked at the multi-port empty container-repositioning problem through leasing and purchasing strategies. Braekers, Janssens, and Caris (2011) 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 (Di Francesco, Lai, and Zuddas 2013). Lu and Mu (2016) 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 (Shintani, Konings, and Imai 2010). Other container studies, such as Chang et al. (2019) and Wang, Lai, and Mohmand (2014) 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. The use of foldable containers can effectively reduce the total volume of empty containers. Hence, Bandara et al. (2015) predicted that by 2035 use of foldable containers in the port of Melbourne, Australia, will lead to an 80% decrease in the number of empty containers. However, only a handful of studies have been conducted on the deployment of the recently developed foldable container.

Konings and Thijs (2001) and Konings (2005) analyzed the advantages and disadvantages of exploiting foldable containers. Shintani, Konings, and Imai (2012) 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 (2013) and Moon and Hong (2016) compared the repositioning costs when foldable containers were used to those when standard containers were used. Myung and Moon (2014) proposed a problem similar to

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that introduced by Moon, Do Ngoc, and Konings (2013) and solved it within polynomial time. Zheng, Sun, and Zhang (2016) 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. (2018) introduced the repositioning problem with foldable containers in an intermodal transportation network. Myung (2017) showed that several mathematical models developed by (Shintani, Konings, and Imai 2010) could be solved within polynomial time.

To our knowledge, Shintani, Konings, and Imai (2010) 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 (2010) 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 study 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 (2010). 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 paper is as follows: We introduce the single depot repositioning problem (SDRP) in Section 2 and expand it to a multi-depot repositioning problem (MDRP) in Section 3. Computational experiments are presented in Section 4, and Section 5 offers conclusions about this study.

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 (2010) 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.

Problem description

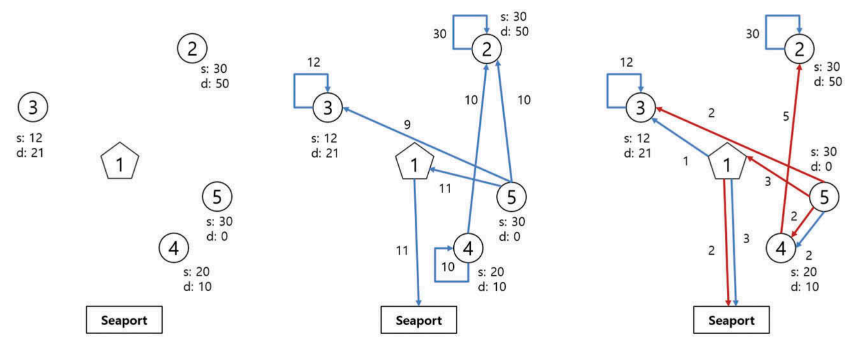
For this study, a hinterland area was assumed to consist of a seaport, an inland depot, and customer nodes (of shippers and consignees). Each customer node was characterized by the supply and demand of empty containers, and a shipping company needed to satisfy customer requests. If the customers' aggregated 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*. The 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, the 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*. 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 1. When compared to Figure 1(b,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.

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.



(a) Example of a supply depot (b) Repositioning plan with standard containers (c) Repositioning plan with mixed containers

Figure 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).

(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.

Descriptions of the model are as follows:

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
$c^R_{i,j}$	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	
$x^F_{i,j}$	Number of folded packs moved from node i to node j, $\forall i,j \in N$
$x^U_{i,j}$	Number of unfolded foldable containers moved from node i To node j, $\forall i,j \in N$
$x^S_{i,j}$	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 mathematical formulation of the SDRP is as follows:

$$\text{Minimize} \sum_{i,j \in N} c^R_{i,j}(x^F_{i,j} + x^U_{i,j} + x^S_{i,j}) + \sum_{i \in N\backslash\{0\}} c^{FU} z_i \quad (1)$$

Subject to

$$\sum_{j \in N}(Fx^F_{i,j} + x^U_{i,j} + x^S_{i,j}) = s_i \qquad \forall i \in N\backslash\{0,1\} \quad (2)$$

$$\sum_{i \in N}(Fx^F_{i,j} + x^U_{i,j} + x^S_{i,j}) = d_j \qquad \forall j \in N\backslash\{0,1\} \quad (3)$$

$$\sum_{i \in N}(Fx^F_{1,i} + x^U_{1,i}) = \sum_{i \in N}(Fx^F_{i,1} + x^U_{i,1}) \quad (4)$$

$$\sum_{i \in N} x^S_{1,i} = \sum_{i \in N} x^S_{i,1} \quad (5)$$

$$\sum_{i \in N\backslash\{0,1\}} \sum_{j \in N}(Fx^F_{i,j} + x^U_{i,j}) = A \quad (6)$$

$$z_1 = F\left|\sum_{j \in N} x^F_{1,j} - \sum_{j \in N} x^F_{j,1}\right| \quad (7)$$

$$z_i = F\sum_{j \in N}(x^F_{i,j} + x^F_{j,i}) \qquad \forall i \in N\backslash\{0,1\} \quad (8)$$

$$x^F_{i,i} = 0 \qquad \forall i \in N \quad (9)$$

$$x^U_{i,i} = x^S_{i,i} = 0 \qquad \forall i \in \{0,1\} \quad (10)$$

$$x^F_{0,i} = x^U_{0,i} = x^S_{0,i} = 0 \qquad \forall i \in N\backslash\{0\} \quad (11)$$

$$x^F_{i,0} = x^U_{i,0} = x^S_{i,0} = 0 \qquad \forall i \in N\backslash\{0,1\} \quad (12)$$

$$x^F_{i,j}, x^U_{i,j}, x^S_{i,j} \in \mathbb{Z}_+ \qquad \forall i,j \in N \quad (13)$$

$$z_i \in \mathbb{Z}_+ \qquad \forall i \in N\backslash\{0\} \quad (14)$$

The objective function (1) minimizes total costs, including those for repositioning as well as folding and unfolding containers, in a hinterland area. Constraints (2) and (3) suggest that the supply and demand of empty containers for each customer node should be satisfied. Constraints (4) and (5) refer to balance equations in an inland depot. Constraint (6) sets the limits of the restricted number of foldable containers in the hinterland area. Constraint (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 (8) denotes every inflow (outflow) of folded packs needed to be unfolded (folded) to meet the demand (supply) of Node *i*. Constraint (9) ensures that reused empty containers cannot be in the folded state. Constraint (10) ensures that containers cannot be reused at an inland depot and seaport. Constraints (11) and (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 (13) and (14) guarantee that all variables are nonnegative integers. The number of constraints increases in direct proportion to the number of nodes.

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 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 the 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. The 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 2 shows a detailed example of the ways the 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.

Shintani, Konings, and Imai (2010) 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 (2010) 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 the 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 the 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 the 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.

The effects of using each folding processes differ. Unlike ADI, through each customer can directly trade empty containers, AII does not permit the movement of empty containers between customer nodes. For this reason, the second minor effect does not

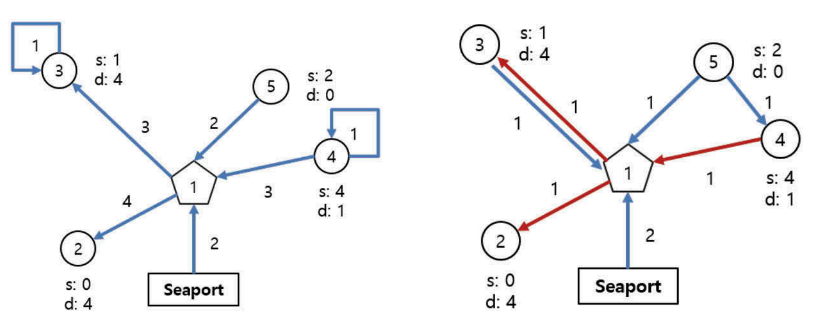
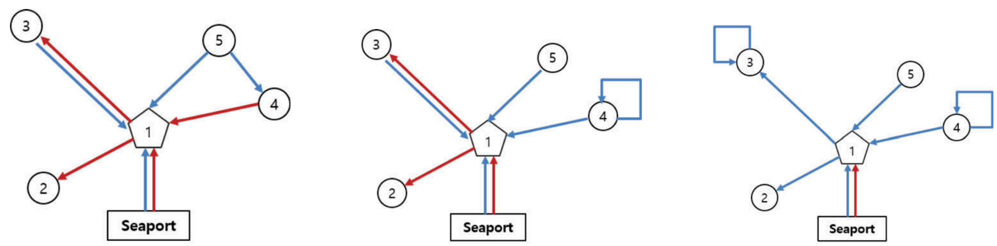


Figure 2. The effects of using foldable containers (red arrow: flow of folded packs, blue arrow: flow of unfolded containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node).



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

Figure 3. Different scenarios (red arrow: flow of folded packs, blue arrow: flow of unfolded containers).

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.

Shintani, Konings, and Imai (2010) presented three different policies with respect to operating an inland depot. The examples of these policies are illustrated in Figure 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, the use of folded packs can save on expenses, and we define these savings as *long distance savings*. Therefore, the 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 important issue.

In this study, 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 the 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:

$$x^F_{i,j} = x^U_{i,j} = x^S_{i,j} = 0 \qquad \forall i,j \in N\backslash\{0,1\}, i \neq j \qquad (15)$$

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

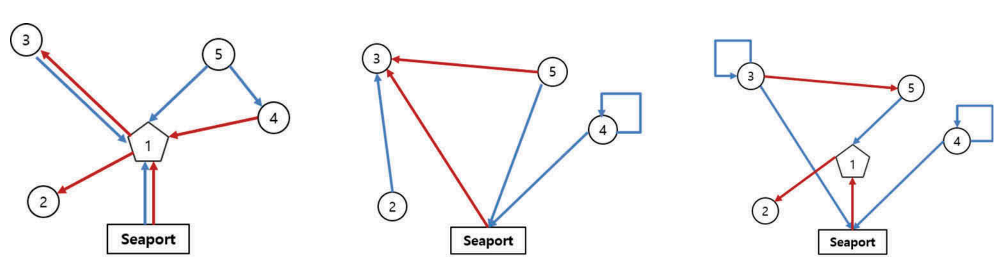
$$x^F_{i,1} = x^F_{1,i} = 0 \qquad \forall i \in N\backslash\{0,1\} \qquad (16)$$

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.

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 a 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 5.

If each depot exploits one type of container 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



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

Figure 4. Different policies (red arrow: flow of folded packs, blue arrow: flow of unfolded containers).

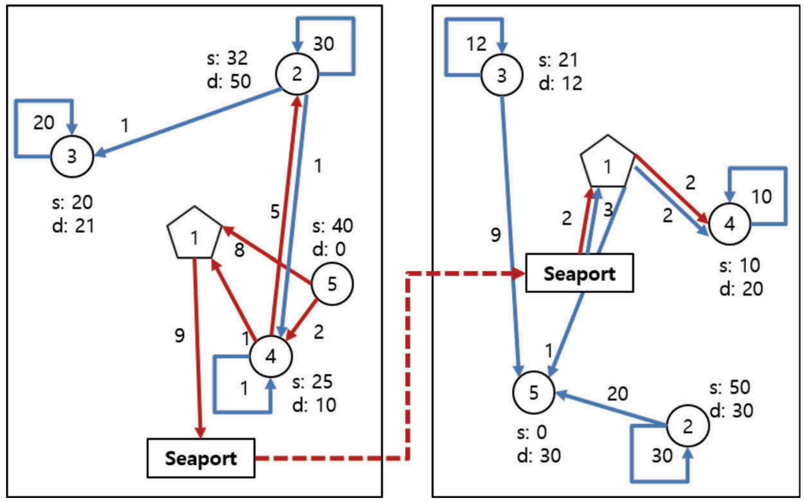


Figure 5. Example of the MDRP (red arrow: flow of folded packs, blue arrow: flow of unfolded containers, dotted arrow: shipped containers, s: supply of empty containers at each customer node, d: demand of empty containers at each customer node).

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. Examples are presented in Figure 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.

Sets, parameters, and variables for the SDRP are expanded by multiple depots. The modified descriptions from the single depot problem are not repeated. Instead, only new definitions are given as follows:

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:

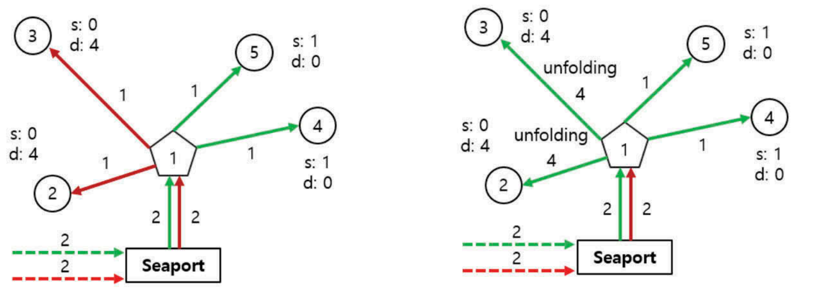
$$\text{Minimize} \sum_{p \in P} \Big[\sum_{i,j \in N_p} c_{i,j,p}^R (x_{i,j,p}^F + x_{i,j,p}^U + x_{i,j,p}^S) + \sum_{i \in N_p} c_p^{FU} z_{i,p} \Big] + \sum_{p \in P \backslash \{s\}} c_p^E (y_p^F + y_p^U + y_p^S) \tag{17}$$

Subject to

$$\sum_{j \in N_p} (F x_{i,j,p}^F + x_{i,j,p}^U + x_{i,j,p}^S) = s_{i,p} \qquad \forall i \in N_p \backslash \{0,1\}, \forall p \in P \tag{18}$$

$$\sum_{i \in N_p} (F x_{i,j,p}^F + x_{i,j,p}^U + x_{i,j,p}^S) = d_{j,p} \qquad \forall j \in N_p \backslash \{0,1\}, \forall p \in P \tag{19}$$

$$\sum_{i \in N_p} (F x_{1,i,p}^F + x_{1,i,p}^U) = \sum_{i \in N_p} (F x_{i,1,p}^F + x_{i,1,p}^U) \qquad \forall p \in P \tag{20}$$



(a) Example of a demand depot under AII

(b) Example of a demand depot under SII

Figure 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).

$$\sum_{i \in N_p} x^S_{1,i,p} = \sum_{i \in N_p} x^S_{i,1,p} \qquad \forall p \in P \qquad (21)$$

$$\sum_{i \in N_p \backslash \{0,1\}} \sum_{j \in N_p} (Fx^F_{i,j,p} + x^U_{i,j,p}) = A_p \qquad \forall p \in P \qquad (22)$$

$$\sum_{i \in N_p} (Fx^F_{1,i,p} + x^U_{1,i,p}) \geq Fy^F_p + y^U_p \qquad \forall p \in P \backslash \{s\} \qquad (23)$$

$$x^F_{i,i,p} = 0 \qquad \forall i \in N_p, \forall p \in P \qquad (24)$$

$$x^U_{i,i,p} = x^S_{i,i,p} = 0 \qquad \forall i \in \{0,1\}, \forall p \in P \qquad (25)$$

$$z_{1,p} = F\left|\sum_{j \in N_p} x^F_{1,j,p} - \sum_{j \in N_p} x^F_{j,1,p}\right| \qquad \forall p \in P \qquad (26)$$

$$z_{i,p} = F\sum_{j \in N_p} (x^F_{i,j,p} + x^F_{j,i,p}) \qquad \forall i \in N_p \backslash \{0,1\}, \forall p \in P \qquad (27)$$

$$\sum_{p \in P \backslash \{s\}} y^F_p = x^F_{1,0,s} \qquad (28)$$

$$\sum_{p \in P \backslash \{s\}} y^U_p = x^U_{1,0,s} \qquad (29)$$

$$\sum_{p \in P \backslash \{s\}} y^S_p = x^S_{1,0,s} \qquad (30)$$

$$y^F_p = x^F_{0,1,p} \qquad \forall p \in P \backslash \{s\} \qquad (31)$$

$$y^U_p = x^U_{0,1,p} \qquad \forall p \in P \backslash \{s\} \qquad (32)$$

$$y^S_p = x^S_{0,1,p} \qquad \forall p \in P \backslash \{s\} \qquad (33)$$

$$x^F_{0,i,p} = x^U_{0,i,p} = x^S_{0,i,p} = 0 \qquad \forall i \in N_p \backslash \{0,1\}, \forall p \in P \qquad (34)$$

$$x^F_{i,0,p} = x^U_{i,0,p} = x^S_{i,0,p} = 0 \qquad \forall i \in N_p \backslash \{0,1\}, \forall p \in P \qquad (35)$$

$$x^F_{0,1,s} = x^U_{0,1,s} = x^S_{0,1,s} = 0 \qquad (36)$$

$$x^F_{1,0,p} = x^U_{1,0,p} = x^S_{1,0,p} = 0 \qquad \forall p \in P \backslash \{s\} \qquad (37)$$

$$x^F_{i,j,p}, x^U_{i,j,p}, x^S_{i,j,p} \in \mathbb{Z}_+ \qquad \forall i,j \in N_p \qquad (38)$$

$$y^F_p, y^U_p, y^S_p \in \mathbb{Z}_+ \qquad \forall p \in P \backslash \{s\} \qquad (39)$$

$$z_{i,p} \in \mathbb{Z}_+ \qquad \forall i \in N_p \qquad (40)$$

The objective function (17) minimizes the total costs between depots including transportation costs, folding and unfolding costs, and shipment costs between Depot s and Depot p. Constraints (18) and (19) denote the supply and demand conditions of empty containers. Constraints (20) and (21) show the inflow and outflow of empty containers at an inland depot should be equal. Constraint (22) explains the restricted number of foldable containers for each node at Depot p. Constraint (23) denotes the number of foldable containers received at a demand depot. Constraints (24) and (25) ensure that reused empty containers are not in the folded state. Constraints (26) and (27) refer to the number of folding and unfolding processes. Constraints (28), (29), and (30) denote the shipped empty containers sent to demand depots that came from supply Depot s. Constraints (31), (32), and (33) ensure the number of empty containers move from a seaport to an inland depot. Constraints (34) and (35) explain that empty containers cannot directly move between a seaport and customer nodes. Constraint (36) denotes that the supply depot cannot receive empty containers from demand depots. Constraint (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.

Computational experiments

We conducted systematic analyses of the 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(R) Core(TM) i5-3570 CPU 3.4 GHz with 8.0 GB of RAM in Windows 10.

Experimental design for the SDRP

Because our study is the extended work of Shintani, Konings, and Imai (2010), experimental designs and parameter values referred to the previous work. Detailed information of a supply depot is shown as follows in which EC is an empty container, EF stands for empty foldable containers, and ES refers to an empty standard container.

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. Six nodes were randomly generated in 300 square kilometers, and supply and demand were also randomly generated between 1 and 40.

In Subsection 2.3, three scenarios and two policies of the hinterland area were introduced. Therefore, total of six combinations were examined for analysis. Total costs were checked to analyze the 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 the 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.

Experimental results for the SDRP

To analyze the effect of 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 7 presents the differences between the total costs 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 (2010), substituting foldable containers for all standard containers could save on total costs substantially. In our experimental results, the total costs also decreased by exploiting foldable containers. However, our results showed that foldable containers were not necessarily needed when α was greater than 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.

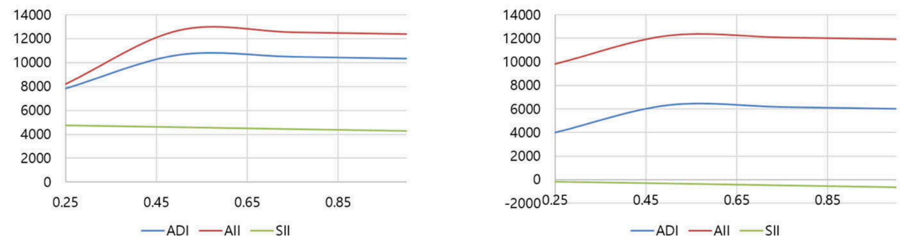
Among cases under the BASIC policy, AII showed the highest optimal number of foldable containers and the greatest cost savings ($\simeq$ 12,700). However, SII had the lowest optimal number of foldable containers and least cost savings ($\simeq$ 4,760). In a notable finding, the optimal value of α for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

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 is illustrated in Figure 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*.

The 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 in costs between the 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 1 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.

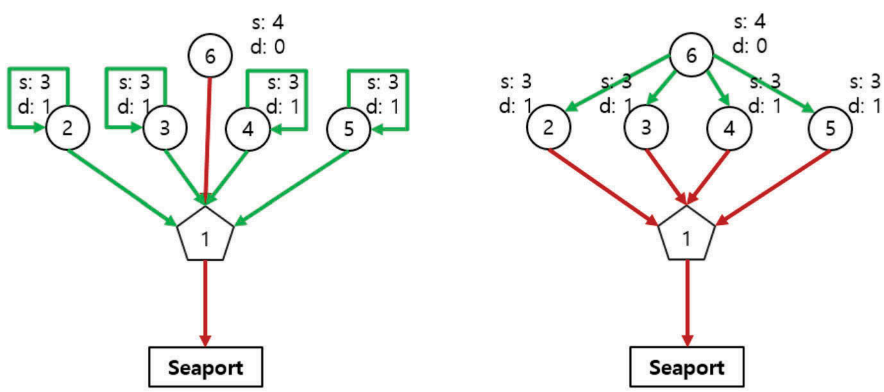
For different scenarios and policies, we checked the α value to calculate the number of foldable containers required in order to incur minimum costs, as shown in Table 2. In the case of BASIC, the α values of Bound (i.e. at the upper bound) and Best (i.e. that yield the lowest cost) were the same. However, as also seen in Table 1, 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



(a) Difference between the total costs using standard containers and those when using mixed containers with BASIC

(b) Difference between the total costs using standard containers and those when using mixed containers with SEAPORT

Figure 7. Relationship between the exploitation ratio (x-axis) and the total costs (y-axis,) in different scenarios under (a) BASIC and (b) SEAPORT policies.



(a) An example considering only major effects

(b) An example considering both effects

Figure 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).

Table 1. 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

Table 2. 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

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 ($\alpha = 0.44$).

To understand the characteristics of effects caused by the 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 the 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.

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 the 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 in the same way as the previous SDRP

Table 3. Relative savings (%) of Bound and Best for different scenarios under different policies and with varying supply and demand ratios.

	Supply & Demand	BASIC		SEAPORT	
Scenario	Ratio	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
All	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

Table 4. Relative savings (%) and the best α value for different nodes under different scenarios and policies.

	ADI		All		SII	
Number of Nodes	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

instances except for the number of nodes. The results are shown in Table 4. 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.

Conclusions

The main contribution of our study 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 study 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. However, because foldable containers have not yet been standardized, rigorous quantitative analysis is challenging. Thus, 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.

Acknowledgments

The authors are grateful for the valuable comments from the editor and anonymous reviewers. This work was supported under the framework of the international cooperation program managed by the National Research Foundation of Korea (2018K2A9A2A06022892, FY2018).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Research Foundation of Korea (NRF) under Grant [2018K2A9A2A06022892].

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