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ECONOMIC BENEFITS OF DEPLOYING FOLDABLE CONTAINERS: REDUCING BUNKER AND CONTAINER MANAGEMENT COSTS IN A MULTI-PORT SHIPPING NETWORK

Summary. This study seeks to explore the effectiveness of employing foldable containers (FLDs) in liner shipping to reduce relocation and the empty containers and bunker costs (BCs) associated with ship operations. This resolves a minimum-cost multi-commodity network flow problem by optimizing container fleet size and empty container relocation in a multi-port shipping service network. Port handling time and sailing speed provided by obtained optimal solutions enable the determination of ship BCs as a secondary step. The numerical experiments demonstrate the comparative effect of FLDs against standard ones on the reduction of the costs of empty containers and containership bunker oil.

1. INTRODUCTION

Global container shipping has significantly grown during the past two decades (United Nations [20]). This growth has resulted in several challenges, including an imbalanced empty container supply due to trade volume differences. Traditionally, shipping companies address this by transferring containers between ports using spare ship capacity. However, this does not generate revenue and incurs container management costs (CMCs). Some container carriers may use foldable containers (FLDs), such as four-in-one designs, instead of standard containers (STDs), in order to minimize the costs associated with relocating empty containers. FLDs can be folded and bundled four high when repositioned, reducing space by 75%, aiding efficient utilization, and lowering the handling burden at ports, meaning they may be more cost-effective than STDs, especially for extreme trade imbalance (TI) lanes.

Another challenge has been an increase in bunker prices over the past two decades (U.S. Energy Information Administration [21]). Containerships consume much fuel that is sensitive to bunker costs (BCs) with regard to sailing speed; slow steaming cuts BCs and meets environmental standards, resulting in longer transit times and lower customer satisfaction. Also, shipping carriers are concerned with higher fixed operational costs and a lower freight rate due to ship overcapacity. Therefore, reducing port dwell time with fewer handling burdens, such as reducing empty volume by using FLDs, facilitates the maintenance of the same sailing schedules, albeit at a slower sailing speed.

Based on these insights, we propose a hypothesis regarding the use of FLDs by which they can lower empty container volumes to be relocated, resulting in fewer CMCs and shorter container handling times while carriers benefit from the above-mentioned effects.

This study aims to demonstrate that the use of FLDs in a container fleet can reduce CMCs and BCs. It employs a two-step procedure to analyze the impact of FLDs. The first step involves optimizing the

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configuration of STDs and FLDs using an existing model introduced by Shintani et al. [15]. This model, known as the container fleet sizing and empty container management problem with FLDs (CFSMP-F), solves a network flow problem for multi-commodity network problems with minimum flow costs. It determines the optimal fleet sizes as well as the allocation and repositioning of STDs and FLDs over a planning horizon, considering fixed shipping routes, port call schedules, ship capacities, transport demands, and other relevant inputs.

This paper is structured as follows: Section 2 surveys previous research on the economic impact of FLDs and addresses the issue of increasing bunker prices. Section 3 outlines the problem, presenting the model framework and underlying assumptions. Section 4 presents the outcomes obtained from numerical experiments. Section 5 summarizes the main findings. The appendix contains details on the model utilized in the numerical experiments, including its framework and equations.

2. RELATED STUDIES

Over the last two decades, studies have focused on lowering container repositioning costs with FLDs. Konings and Thijs [5] and Konings [6] examined FLD viability and shipping market conditions. Shintani et al. [15] observed that a mixed fleet of STDs and FLDs offers advantages in liner shipping. Their pioneering research on FLDs in shipping networks urged the use of hybrid STD/FLD fleets to reduce investment risk. Myung and Moon [9] examined multi-port, multi-period planning with STDs, FLDs, and routes. Moon and Hong [8] transferred containers between ports using STDs and FLDs using a model for fold-capable ports. Wang et al. [25] analyzed ship type, fleet size, empty container relocation, and FLD use on specific routes, promoting long-term leased fleets. No researchers have explored the potential use of FLDs to lower bunker consumption by reducing the time taken for empty container handling at ports. Despite tier variations affecting viability, no criteria-based FLD design comparison exists. This study fills these gaps.

Our attention now turns to the realm of sailing speed and its efficiency. Over a decade, this matter gained industry and academic attention due to increased BCs, emissions concerns, and schedule disruption. Notteboom and Vernimmen [10] addressed bunker price impact on containerships, Qi and Song [14] scheduled liners for fuel reduction, and Wang and Meng [23] optimized sailing speed with transshipment. Psaraftis and Kontovas [13] maximized speed under routing, Doudnikoff and Lacoste [1] studied low-sulfur restrictions, and Wang and Meng [24] considered sailing speed discrepancies. Fagerholt et al. [2] optimized routing for sulfur compliance, Fagerholt and Psaraftis [3] tackled the sulphur emission control areas, and Vad Karsten et al. [4] balanced sailing speed and bunkering. Wang and Chen [22] studied refueling, Wen et al. [26] optimized routes, and Wu [27] proposed optimal sailing speed models. Zheng et al. [28] examined frequency constraints.

While previous studies have demonstrated the cost-saving potential of FLDs, none have delved into the economic ramifications of decreasing bunker consumption through slower sailing speeds facilitated by efficient empty container handling at ports using FLDs. This notable gap underscores the pioneering nature of our study, which assesses the potentially transformative economic advantages of the synergistic integration of FLD deployment and sailing speed reduction—a previously unexplored area. Consequently, our study is the first to fill this significant gap in the current literature.

3. PROBLEM DESCRIPTION

We optimized empty container movement in a multi-port shipping-service network (MPSN) framework, obtaining insights into port dwell time, sailing speed, and BCs. We compared the economic benefits of FLDs by evaluating BCs and CMCs in various STD and/or FLD scenarios.

3.1. CFSMP-F outline

This section outlines the container fleet and repositioning model built by Shintani et al. [15] called CFSMP-F, which minimizes CMCs through optimal container fleet sizing and empty container movements. The model covers multiple container types, like STDs, FLDs, and leased STDs, in a multi-commodity flow model, ensuring container flow conservation. CFSMP-F optimizes repositioning for specific routes, considering TI and traffic fluctuations. Container states (STD/FLD, laden/empty, own/leased) detail movements.

The overall costs associated with FLDs and STDs encompass the following:

- folding/unfolding (F/UF) FLDs at ports, along with container inspection;
- exploitation of FLDs and STDs;
- storage of empty FLDs and STDs at ports and their repositioning between ports;
- short-term (spot) leasing STDs, including their handling and return.

Aligned with industry norms, we assume consistent weekly cargo fulfilment. A shortage of company-owned fleets prompts short-term leasing. Expanding the owned fleet is one way to cut CMCs with fewer leases. This involves owned and leased fleet size choices. The CFSMP-F includes long-term leased containers as part of the owned fleet. Notably, owned fleet size is constant as ownership decisions are strategic, unlike leasing. Practical owned fleet size considers factors like F/UF costs, owned inventory costs, and repositioning. The CFSMP-F simplifies decisions by focusing on STD containers for leasing.

The CFSMP-F is based on the following assumptions:

(1) Short-term (or spot) leased containers are only STDs.
(2) Container leasing and return are made at the same location (port). The leasing cost covers expenses for the entire leasing period and the associated pick-up and return of leased containers, including port loading and unloading fees.
(3) FLDs and STDs are 20 ft; 40 ft is large for an STD but small for an FLD.
(4) All cargo transportation demands are fully satisfied.
(5) Certain origins and destinations of laden containers are located deep inside of port hinterlands.
(6) All containers are considered under the control of a single shipping line.
(7) Appendix A presents the complete model formulation to avoid cluttering the main document with lengthy formulations of the CFSMP-F.

3.2. Sailing speed

After CFSMP-F's fleet optimization, we analyzed container flow variables for handling time. Average sailing speed was derived from the total port calling time across the route.

In strategic decision-making, the liner company determines these parameters:

$$v(n) = \frac{D}{24\{RT - P(n)\}} \quad \forall n \in N \tag{1}$$

$$P(n) = \sum_{i \in I} \left\{ \frac{LU_i(\gamma_i^n)}{qc_i(n) \cdot h_i} + p_i^d + p_i^a \right\} / 24 \quad \forall n \in N \tag{2}$$

$$LU_i(t) = \sum_{h \in I} E_{hi}(t - \beta_{hi}) + \sum_{j \in I} E_{ij}(t) + \sum_{h \in I} EX_{hi}(t - \beta_{hi}) + \sum_{j \in I} EX_{ij}(t)$$
$$+ \sum_{h \in I} EY_{hi}(t - \beta_{hi}) + \sum_{j \in I} EY_{ij}(t) + \sum_{h \in I} F_{hi}(t - \beta_{hi}) + \sum_{j \in I} F_{ij}(t) \quad \forall t \in T, i \in I \tag{3}$$

$$qc_i(n) = [k_0 \cdot ln\{LU_i(\gamma_i^n)\} - k_1] \quad \forall n \in N, i \in I \tag{4}$$

where TEU stands for 20 ft equivalent unit and I denotes the set of calling ports. The specific roundtrip time (RT; days), as a multiple of seven for the weekly shipping route, consists of the total sailing time $D/\{24v(n)\}$ (days) and the total port time $P(n)$ (days), where D (nm) is the total sailing distance on the shipping route, the index n is the n-th voyage and N is the set of voyage numbers. Eq. (1) determines $v(n)$, the average sailing speed (knots) on the n-th voyage, to maintain RT. $P(n)$ is obtained using Eq. (2), where $LU_i(\gamma_i^n)$ (TEUs) is the number of containers (laden/empty) to be handled (loaded/unloaded) at port i at time γ_i^n, γ_i^n is the ship calling time at port i on the n-th voyage, $qc_i(n)$ is the number of quay cranes assigned to cargo handling at port i on the n-th voyage, h_i (TEUs/h) is the number of containers handled per hour per quay crane at port i, and p_i^d/p_i^a (h) are the standby time for pilotage (departure/arrival) at port i. The number of quay cranes $qc_i(n)$ is based on how many containers are handled at port i on the n-th voyage. Eq. (3) defines $LU_i(t)$ using container flows between port i and other ports. It is based on the numbers of laden and empty containers—$F_{ij}(t)$, $E_{ij}(t)$, $EX_{ij}(t)$ and $EY_{ij}(t)$ (TEUs)—carried from port i at time t. These variables represent owned and leased laden containers, empty STDs, folded/bundled empty FLDs, and erected empty FLDs departing from port i for port j at time t.

The World Bank [19] presented a regression model (Eq. (4)) that estimates that quay cranes per move per port call, k_0 and k_1, are constants with high accuracy (R^2 = 0.5993).

3.3. Bunker cost (BC)

Following Suzuki [18], BC is defined in this study using the following equations:

$$BC(n) = C^B \cdot CO(n) \quad \forall n \in N \tag{5}$$

$$CO(n) = k_2 \cdot \{DS - (1 - k_3 \cdot LF) \cdot DW\} \cdot D \cdot DS^{-\frac{1}{3}} \cdot \{v(n)\}^2 \quad \forall n \in N \tag{6}$$

$$DS = 1.37 \cdot DW + 1{,}660 \tag{7}$$

$$DW = 10.8 \cdot CAP + 12{,}400 \tag{8}$$

The bunker cost $BC(n)$ (US$) of the n-th voyage is defined using Eq. (5), where C^B is the bunker price in US$/metric tonne and $CO(n)$ (metric tonnes), as bunker consumption depends on the average sailing speed $v(n)$ (Eq. (6)). DS, DW, and D represent the ship's displacement, deadweight, and sailing distance, respectively, LF is the average load factor, and k_2/k_3 are constants. DS depends on DW (Eq. (7)), while DW is given by Eq. (8), where CAP is the ship's carrying capacity in TEUs. The square function in Eq. (6) shows that faster sailing results in much higher bunker consumption.

In Eq. (6), $CO(n)$ is estimated using DS and DW, which indirectly represent resistance force, along with $v(n)$. This study simplifies the model without compromising insights; however, future research may utilize more nuanced resistance modelling to enhance bunker consumption estimates.

4. NUMERICAL EXPERIMENTS

This section presents experiments exploring the impact of FLDs on CMCs and BCs. Our computer setup included a 64-bit Windows 10 system, Intel Xeon CPU E3-1246 v3, 3.5 GHz, and 32 GB RAM. We used Gurobi Optimizer 9.1.1 and Python 3.5 to solve the CFSMP-F.

We focused on a weekly shipping route (trade lane) between Asia and Europe to demonstrate a realistic geographical setting. We assumed the following route itinerary: Busan–Ningbo–Shanghai–−Rotterdam–Hamburg–Antwerp–Southampton–Yantian–Shanghai–Busan (11 ships deployed covering a distance of 26,038 nm $[D]$ in an RT of 77 days). This shipping route refers to that of the Ocean Network Express [11].

4.1. Parameter settings

The parameter settings were as follows:
(1) Planning horizon ($|T|$): 52 weeks (or one year); (2) number of FLD tiers (NT): four to six (corresponding to different types of FLDs, from four-in-one to six-in-one); (3) ship's carrying capacity (CAP): 15,000 TEUs; (4) time taken for containers to complete turnaround within the hinterland of port i (α_i): one week for the hinterlands of all ports; (5) transit time from port i to port j (β_{ij}): one to 11 weeks, depending on the distance between the OD port pair; (6) storage capacity at port i (H_i): double the weekly throughput at each port, which is set as the basic capacity; (7) exploitation cost of a container over a period of 52 weeks: CF^{FLD} = (US$624, 936 and 1,248)/TEU for FLD and CF^{STD} = US$312/TEU for STD; an FLD-type container costs twice as much as an STD-type container, which is set as the basic exploitation cost; (8) F/UF cost at port i (C_i^{FU}): US$100/process for all ports; (9) storage cost at port i:

C_i^S = US\$7/TEU/week for all ports; (10) repositioning cost from port i to port j: C_{ij}^R = (US\$273 to US\$1,003)/TEU, according to the OD port pair; (11) leasing cost from port i to port j: C_{ij}^L = (US\$442 to 1,652)/TEU according to the OD port pair; includes relevant transportation and handling costs; (12) the weekly volume of cargo traffic, comprising both inbound and outbound shipments within the trade lane: 15,000 TEUs (this case occurs when trade volumes in different directions are balanced between the Asian and European regions); (13) the values of the four constants for calculating the number of quay cranes and bunker consumption: k_0 = 1.1974, k_1 = 5.3309, k_2 = 1.4226 × 10^{-7}, and k_3 = 0.65; (14) bunker price (C^B): 600 (US\$/metric tonne); and (15) number of containers handled per hour per quay crane at port i (h_i): 25 (TEUs/h) for all ports.

Section 4.3 details the *NT*. Ship capacity (3) and transit time (5) were taken from the Ocean Network Express [11]. Uniform travel time was used for ports due to limited data. Cost coefficients (6)–(8) were adapted from Shintani et al. [15]. Moreover, we assumed that all port-related costs, such as F/UF (8) and storage (9), were the same due to limited data. Repositioning cost (10) considers ship and port costs (CH = US\$100/TEU; Shintani et al. [16]). In the current study, (10) was defined as ship operating cost (CT = 131,721.4 / CAP + 64.5; Wang and Meng [23]) with transit time. Leasing cost (11) was (HR = US\$48/TEU/week; Lun et al. [7]), including hiring and handling. It is commonly understood that the average load factor hovers around 0.7. Nevertheless, in scenarios with balanced trade, Equation (12) was modified to achieve a load factor of 0.5. This adjustment ensured that the ship's carrying capacity did not limit the relocation of containers, regardless of significant TI in shipment volume and seasonal demand. Constants (13) were reflected from the World Bank [19] and Suzuki [18]. Bunker price data (14) was from Ship & Bunker [17]. Quay crane productivity (15) were based on Pernia and Barrons [12].

4.2. Transportation demands between ports

To define port-to-port traffic, we considered TI, as it highlights FLD benefits. We explored (1:1), (2:1), and (3:1) TI ratios (Table 1). For instance, in the (2:1) case, 780,000 TEUs were transported in 52 weeks: 520,000 TEUs from Asia to Europe and 260,000 TEUs from Europe to Asia. Additionally, seasonal trends were studied using a simulated pattern (Fig. 1). Given limitations in accessing data from shipping companies, we employed a uniform random number distribution to simulate traffic volumes, subsequently adjusting them based on the TI ratios. We obtained weekly cargo traffic per voyage by multiplying the total traffic volume and TI ratios. Table 2 shows port traffic under (1:1) TI and other ratios.

4.3. Number of tiers of foldable containers

This study focused on three FLD designs: four-, five-, and six-in-one. *NT* signifies the number in "*-in-one." For example, *NT* = 4 corresponds to four-in-one. Notably, prior research has not explored the economic benefits of varying *NT*. Thus, the current experiments cover three FLD designs: four-in-one, five-in-one, and six-in-one.

4.4. Experimental design

We performed 27 experiments on a shipping route, varying TI, NT (FLD tiers), and CF (FLD cost). Instance IDs reflected the configuration (e.g., "31-4-x4" meant TI – 3:1, NT– four-in-one, CF – quadruple STD cost). Fleet compositions included STU (STDs), FLU (FLDs), and MIX (both). CFSMP-F solved MIX by adding FS^{FLD} = 0 for STU, FS^{STD} = 0 for FLU.

We also explored the geographical impact by adjusting RT from base (77 days) to 63 and 49 days, keeping other factors constant. This helped us assess the effect of varying RT on FLD performance.

Table 1
Annual cargo traffic between two regions for each trade imbalance (TI)

TI	Asia/Europe	Europe/Asia
1:1	390,000	390,000
2:1	520,000	260,000
3:1	585,000	195,000
Total (in TEUs)	780,000	

Table 2
Port weekly throughput with balanced trade (1:1)

Region	Port	Export	Import
Asia	Busan	944	991
	Ningbo	901	942
	Shanghai	937	927
	Yantian	971	887
Europe	Rotterdam	902	1023
	Hamburg	946	954
	Antwerp	975	880
	Southampton	924	896
Total (in TEUs)		7500	7500

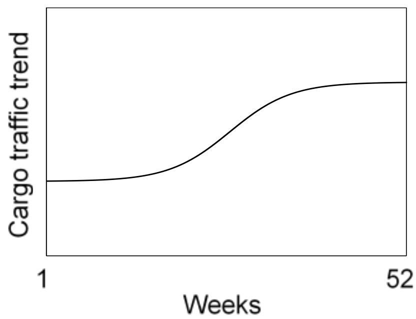


Fig. 1. Cargo traffic trend

4.5. Analyses

We evaluated how FLD use in container fleets, such as FLU, and MIX, is more efficient than STU in container shipping by comparing them in terms of BCs and CMCs.

4.5.1. Number of tiers of foldable containers

Fig. 2 clearly indicates that the BC gaps between STU and MIX/FLU widened with an increase in NT and a decrease in RT. In addition, MIX/FLU resulted in a maximum reduction of BC by approximately 2.5% (RT = 77 days) to 10% (RT = 49 days). Additionally, a similar reduction trend of BC between MIX and FLU occurred, which indicates that MIX and FLU can significantly reduce BCs for shorter RTs. BCs also decreased with lower TI.

4.5.2. Comparison with the total shipping operation cost (i.e., the sum of BC and CMC)

Next, we examined the effect of the use of FLD on the total service costs of container liners, including BCs and CMCs (Fig. 3). CMCs were more sensitive than BCs with FLDs to TI, NT, and CF across three

RTs. The reduction ratio of CMCs was particularly significant. Interestingly, as RT decreased, the CMC gap between MIX/FLU and STU decreased, while the BC gap expanded.

As TI increased, the total costs, including BCs and CMCs, also increased. Notably, when CF was high, MIX was preferred over FLU due to the increase in the exploitation cost of the FLD within the CMCs of FLU, which consisted solely of FLDs. Furthermore, in the case of 'CFx4', FLU resulted in no less total cost than STU in any TI scenario, which indicates that FLD did not always reduce the total cost. In other words, FLD is useful for longer RTs.

4.5.3. Average sailing speed and sailing/port times

Fig. 4 shows the correlation between the average sailing speed and sailing/port times. As discussed in Section 3.2, the proportion of sailing time to port time (mainly container handling time at ports) in a specific RT significantly influences sailing speed. Particularly, under the assumption that cargo demands between OD port pair remain constant regardless of RT, a decrease in RT led to an increase in the disparity in sailing speed between MIX/FLU and STU, especially when NTs were large because large NTs led to more CMC savings since more empty FLDs were folded and bundled as a single STD. Consequently, the port dwell time with MIX and FLU can be shortened due to the lesser STD equivalent units, which results in a slower sailing speed subject to the same voyage time.

When RT decreased from 77 to 63 and 49 days (Figs. 4(b) and (c)), a relative increase was observed in the port dwell time over the entire voyage duration. In these scenarios, although the absolute value of reduced port time was the same as that for the base RT (77 days), the relative effect of MIX and FLU in reducing port time grew with the decrease in RT. Consequently, this led to a decrease in sailing speed. Notably, less RT corresponded to a shorter sailing distance, which resulted in smaller BCs even at the same sailing speed.

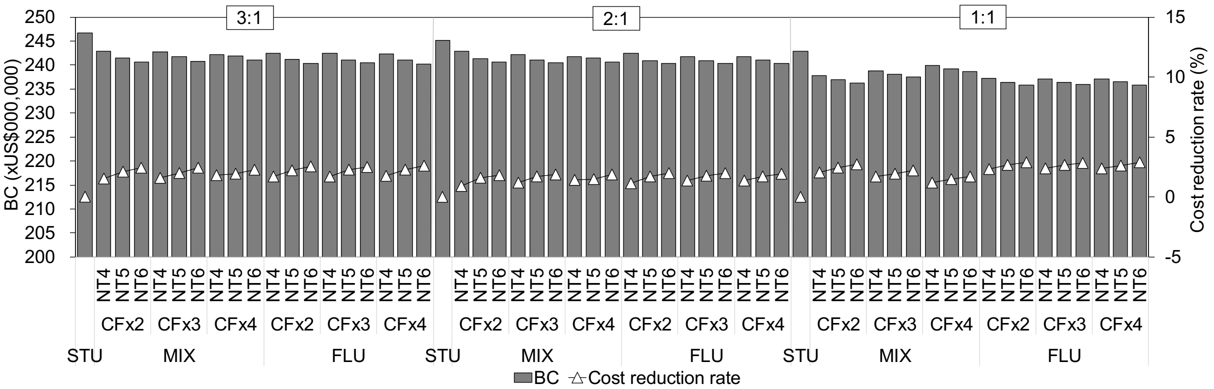
5. CONCLUSIONS

This study examined FLDs' effects on CMCs and BCs, unlike previous studies that focused on CMC reduction and ship sailing speed. We used the CFSMP-F model to optimize MPSN container fleet size and repositioning using a minimum-cost multi-commodity network flow problem. Building upon the findings of the CFSMP-F, which indicated that FLDs can reduce CMCs under specific circumstances (Shintani et al. [15]), this study employed an analytical model to ascertain ship sailing speed, which minimized BCs. We conducted this study to investigate how FLDs affect both CMCs and BCs.

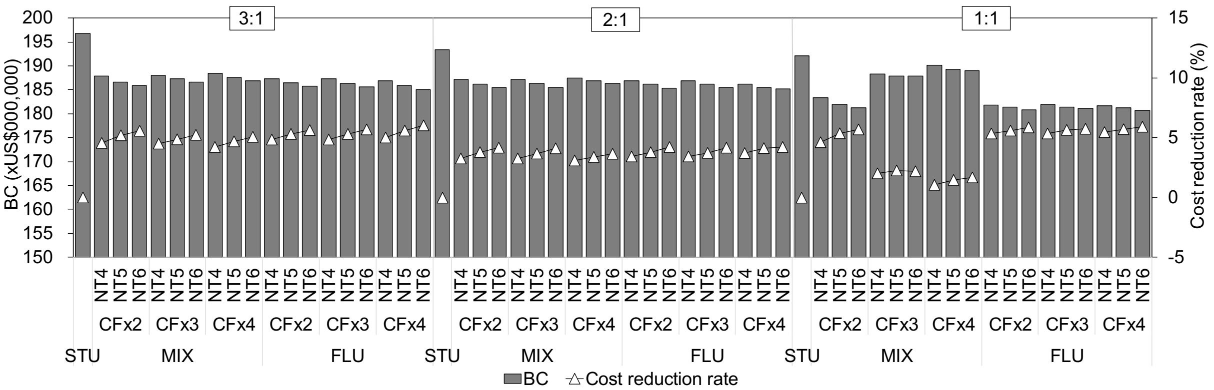
We conclude the following: FLDs can reduce empty container port handling time across shipping routes, especially short-distance routes with high TI ratios. The mixed fleet of FLDs and STDs lowers shipping costs, especially for shorter routes. FLDs speed up ship handling at port in the MIX fleet configuration, slowing ship sailing speed while maintaining the port calling schedule. Finally, FLD use reduces bunker consumption, resulting in lower emissions.

This study indicates the green shipping cost-reduction potential of FLDs. To reduce investment risk, shipping companies may initially deploy a few FLDs. If FLDs meet their expectations, they will gradually expand FLD deployment to an optimal MIX fleet composition.

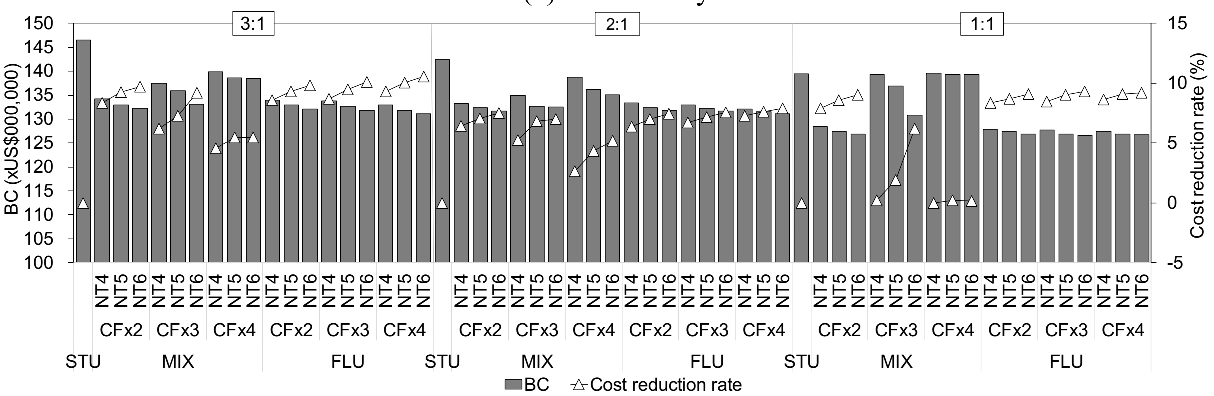
Of note, the proposed approach may not provide the optimal solution for container and ship operations that minimizes the total cost because of the recursive nature underlying the first and second steps of the solution procedure. That is, changes in ship service schedules in the second step may alter the container flow network, which is the basis of container movement representation in the CFSMP-F model in the first step for the container fleet operational decision-making by varying BC-dependent repositioning costs resulting from the sailing speed determination in the second step.



(a) RT = 77 days

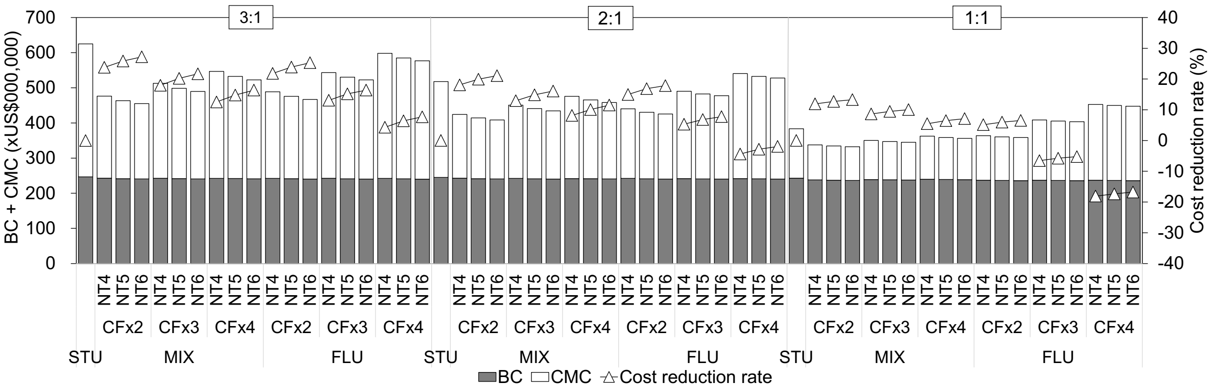


(b) RT = 63 days

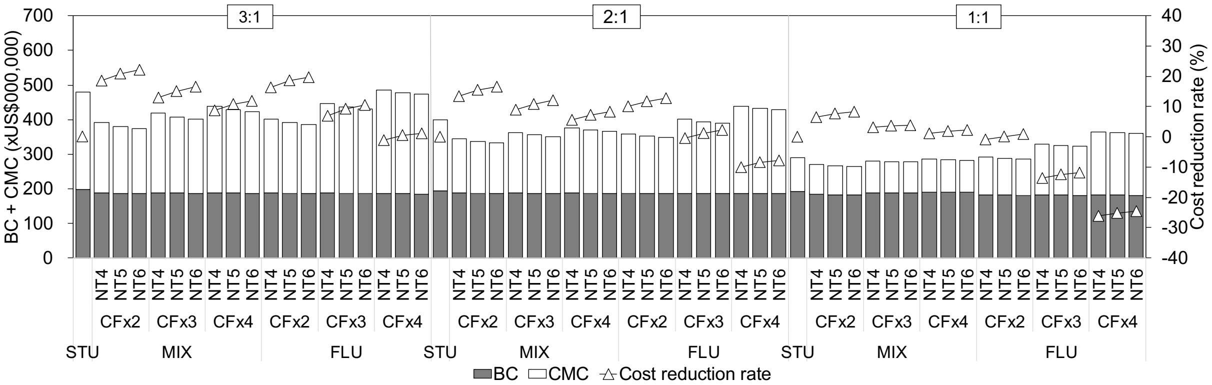


(c) RT = 49 days

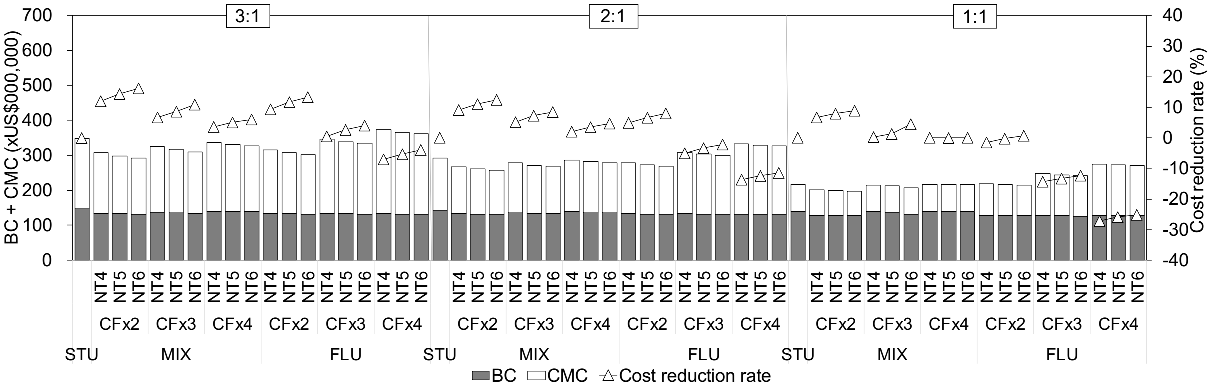
Fig. 2. Comparison of BCs



(a) RT = 77 days

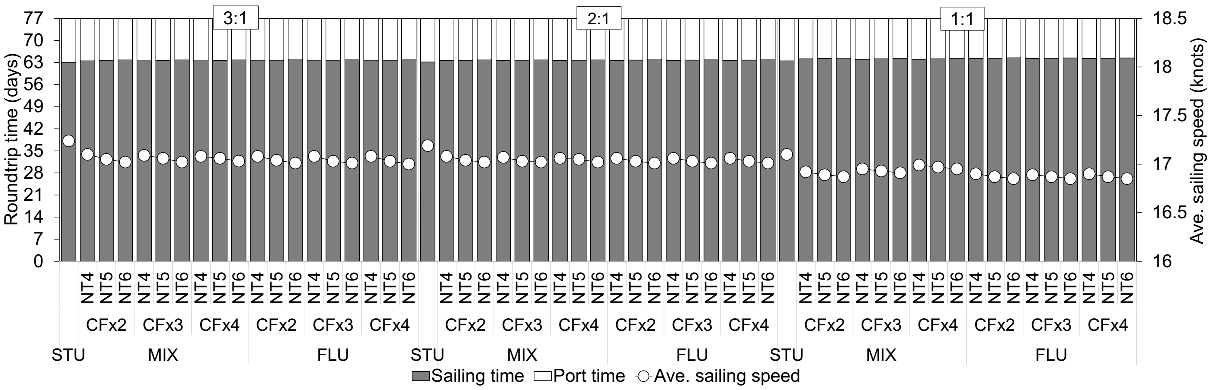


(b) RT = 63 days

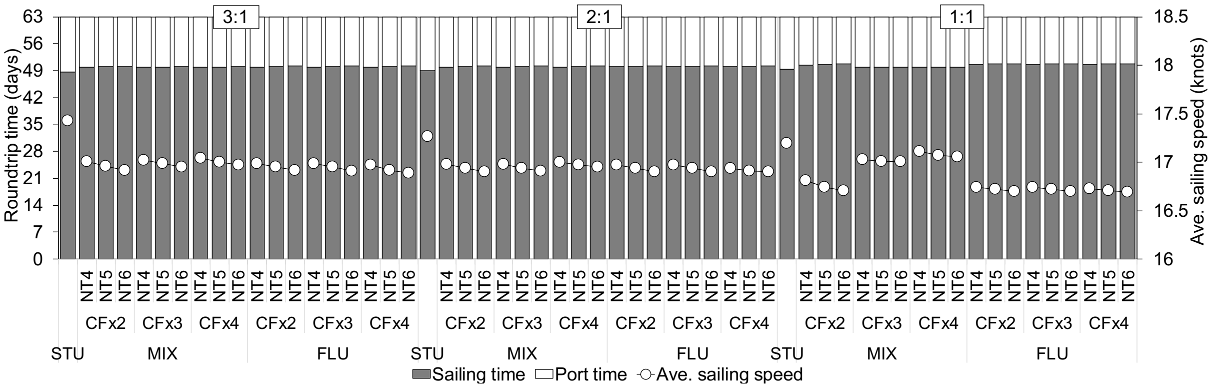


(c) RT = 49 days

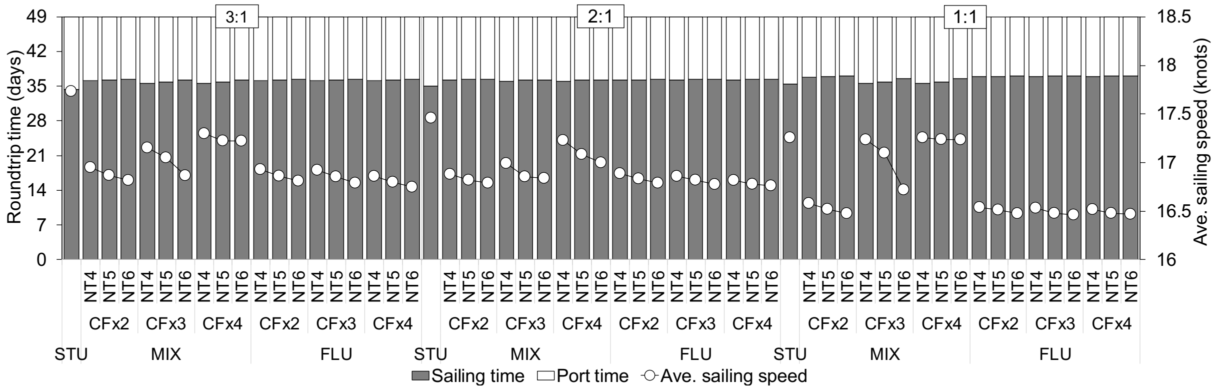
Fig. 3. Comparison of BCs and CMCs



(a) RT = 77 days



(b) RT = 63 days



(c) RT = 49 days

Fig. 4. Average sailing speed and sailing/port times

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Appendix

The study utilized the following notation and formulation:

Notation

Sets

I: set of calling ports in a shipping service network; T: set of planning horizon (chronological time)

Parameters

NT: Number of FLD tiers (designs of FLD-type); CAP: ship's carrying capacity; α_i: duration that a container spends in the hinterland of port i for either import or export; β_{ij}: transit time from port i to port j; C^{STD}: exploitation cost of owned STDs over the planning horizon; C^{FLD}: exploitation cost of FLDs over the planning horizon; C_{ij}^{R}: repositioning cost associated with transporting an STD or a unit of folded and bundled FLDs from port i to port j; C_i^S: storage cost incurred for an STD or a unit of folded and bundled FLDs at port i; C_{ij}^L: leasing cost associated with renting a container for transport from port i to port j; C_i^{FU}: F/UF cost of an FLD at port i; C_{ij}^T: transport cost for moving a container from port i to port j; C_i^H: handling cost, including loading or unloading costs, at port i per container; C_{ij}^{LL}: container hire cost depending on the RT between ports i and j per container; H_i: storage capacity of a container terminal at port i; $F_{ij}(t)$: quantity of laden containers (both owned and leased) departing from port i at time t for port j, considering cargo traffic

Decision variables

FS: quantity of owned STDs; FF: quantity of FLDs; $E_{ij}(t)$: count of empty owned STDs being transported by ships departing from port i at time t for port j; $EX_{ij}(t)$: quantity of folded and bundled empty FLDs transported by ships leaving port i at time t for port j; $EY_{ij}(t)$: quantity of erected empty FLDs transported by ships leaving port i at time t for port j; $S_i(t)$: quantity of empty owned STDs stored at port i at time t; $SX_i(t)$: number of folded and bundled empty FLDs stored at port i at time t; $SY_i(t)$: quantity of erected empty FLDs stored at port i at time t; $L_{ij}(t)$: quantity of leased STD-type containers to be utilized for transport departing from port i at time t for port j; $FU_i(t)$: quantity of empty FLDs to be folded or unfolded at port i at time t.

Auxiliary variables associated with the decision variables

$B_{ij}(t)$: quantity of laden owned STDs transported from port i for port j at time t; $BYY_{ij}(t)$: quantity of laden FLDs transported from port i to port j at time t; $D_i(t)$: total number of laden-owned STDs imported to port i at time t; $DYY_i(t)$: total number of laden FLDs imported to port i at time t; $G_i(t)$: number of empty owned STDs repositioned by ships to port i at time t; $GYY_i(t)$: total number of empty FLDs repositioned by ships to port i at time t; $N_i(t)$: total number of empty owned STDs to be dispatched to shippers (exporters) in the hinterland from port i at time t, equivalent to the total containers to be exported; $NYY_i(t)$: total number of empty FLDs to be sent to shippers (exporters) in the hinterland from port i at time t, also matching the total containers to be exported; $O_i(t)$: total number of empty owned STDs repositioned by ships from port i at time t; $OYY_i(t)$: total number of empty FLDs repositioned by ships from port i at time t; $R_i(t)$: number of empty owned STDs for return by consignees (importers) in the hinterland of port i at time t; the total number of containers to be imported; $RYY_i(t)$: number of empty FLDs earmarked for return by consignees (importers) in the hinterland of port i at time t, also matching the total containers to be imported.

Notably, the following symbols are auxiliary variables for STDs: $B_{ij}(t)$, $D_i(t)$, $G_i(t)$, $N_i(t)$, $O_i(t)$ and $R_i(t)$. Additionally, auxiliary variables aim at conserving the quantity of FLDs in the network, including $EYY_{ij}(t)$, $BYY_{ij}(t)$, $SYY_{ij}(t)$, $DYY_{ij}(t)$, $GYY_{ij}(t)$, $NYY_{ij}(t)$, $OYY_{ij}(t)$ and $RYY_{ij}(t)$.

Formulation

The following constitutes the formulation:

$$\text{Minimize } C^{STD}FS + C^{FLD}FF + \sum_{t\in T}\sum_{i\in I}\sum_{j\in I} C_{ij}^{R}\{E_{ij}(t) + EX_{ij}(t) + EY_{ij}(t)\}$$
$$+ \sum_{t\in T}\sum_{i\in I} C_i^{S}\{S_i(t) + SX_i(t) + SY_i(t)\} + \sum_{t\in T}\sum_{i\in I}\sum_{j\in N} C_{ij}^{L} L_{ij}(t)$$
$$+ \sum_{t\in T}\sum_{i\in I} C_i^{FU} FU_i(t) \tag{9}$$

Subject to

$$S_i(t) = S_i(t-1) + R_i(t) + G_i(t) - N_i(t) - O_i(t) \;\; \forall t \in T, i \in I, \tag{10}$$

$$SYY_i(t) = SYY_i(t-1) + RYY_i(t) + GYY_i(t) - NYY_i(t) - OYY_i(t) \;\; \forall t \in T, i \in I, \tag{11}$$

$$R_i(t) = D_i(t-\alpha_i) \;\; \forall t \in T, i \in I, \tag{12}$$

$$RYY_i(t) = DYY_i(t-\alpha_i) \;\; \forall t \in T, i \in I, \tag{13}$$

$$D_i(t) = \sum_{h\in I} B_{hi}\big(t-\beta_{ij}\big) \;\; \forall t \in T, i \in I, \tag{14}$$

$$DYY_i(t) = \sum_{h\in I} BYY_{hi}\big(t-\beta_{ij}\big) \;\; \forall t \in T, i \in I, \tag{15}$$

$$G_i(t) = \sum_{h\in I} E_{hi}\big(t-\beta_{hj}\big) \;\; \forall t \in T, i \in I, \tag{16}$$

$$GYY_i(t) = \sum_{h\in I} EYY_{hi}\big(t-\beta_{hj}\big) \;\; \forall t \in T, i \in I, \tag{17}$$

$$O_i(t) = \sum_{j\in I} E_{ij}(t) \;\; \forall t \in T, i \in I, \tag{18}$$

$$OYY_i(t) = \sum_{j\in I} EYY_{ij}(t) \;\; \forall t \in T, i \in I, \tag{19}$$

$$N_i(t) = \sum_{j\in I} B_{ij}(t+\alpha_i) \;\; \forall t \in T, i \in I, \tag{20}$$

$$NYY_i(t) = \sum_{j\in I} BYY_{ij}(t+\alpha_i) \;\; \forall t \in T, i \in I, \tag{21}$$

$$L_{ij}(t) = F_{ij}(t+\alpha_i) - B_{ij}(t+\alpha_i) - BYY_{ij}(t+\alpha_i) \;\; \forall t \in T, i \in I, j \in I, \tag{22}$$

$$S_i(t) + SX_i(t) + SY_i(t) \le H_i \;\; \forall t \in T, i \in I, \tag{23}$$

$$FS = \sum_{i\in I}\{S_i(0) + R_i(1) + G_i(1)\}, \tag{24}$$

$$FF = \sum_{i\in I}\{SYY_i(0) + RYY_i(1) + GYY_i(1)\}, \tag{25}$$

$$EY_{ij}(t) = EYY_{ij}(t) - NT \cdot EX_{ij}(t) \;\; \forall t \in T, i \in I, j \in I, \tag{26}$$

$$SY_i(t) = SYY_i(t) - NT \cdot SX_i(t) \;\; \forall t \in T, i \in I, \tag{27}$$

$$FU_i(t) \geq SYY_i(t-1) - SY_i(t-1) + \sum_{h \in I}\{EYY_{hi}(t) - EY_{hi}(t)\}$$
$$-SYY_i(t) + SY_i(t) - \sum_{j \in I}\{EYY_{ij}(t) - EY_{ij}(t)\} \;\; \forall t \in T, i \in I, \tag{28}$$

$$-FU_i(t) \leq SYY_i(t-1) - SY_i(t-1) + \sum_{h \in I}\{EYY_{hi}(t) - EY_{hi}(t)\}$$
$$-SYY_i(t) + SY_i(t) - \sum_{j \in I}\{EYY_{ij}(t) - EY_{ij}(t)\} \;\; \forall t \in T, i \in I, \tag{29}$$

$$\sum_{q=2}^{|I|}\{E_{1q}(t) + EX_{1q}(t) + EY_{1q}(t) + F_{1q}(t)\}$$
$$+\sum_{p=3}^{|I|}\sum_{q(\neq p)=2}^{p-1}\{E_{pq}(t-\beta_{p1}) + EX_{pq}(t-\beta_{p1}) + EY_{pq}(t-\beta_{p1}) + F_{pq}(t-\beta_{p1})\}$$
$$\leq CAP \;\; \forall t \in T, \tag{30}$$

$$\sum_{q(\neq i)=1}^{|I|}\{E_{iq}(t) + EX_{iq}(t) + EY_{iq}(t) + F_{iq}(t)\}$$
$$+\sum_{p=1}^{i-1}\sum_{q(\neq p)=i+1}^{|I|}\{E_{pq}(t-\beta_{pi}) + EX_{pq}(t-\beta_{pi}) + EY_{pq}(t-\beta_{pi}) + F_{pq}(t-\beta_{pi})\}$$
$$+\sum_{p=i+2}^{|I|}\sum_{q(\neq p)=i+1}^{p-1}\{E_{pq}(t-\beta_{pi}) + EX_{pq}(t-\beta_{pi}) + EY_{pq}(t-\beta_{pi}) + F_{pq}(t-\beta_{pi})\}$$
$$\leq CAP \;\; \forall t \in T, i \in I\backslash\{1, |I|\}, \tag{31}$$

$$\sum_{q=1}^{|I|-1}\{E_{|I|q}(t) + EX_{|I|q}(t) + EY_{|I|q}(t) + F_{|I|q}(t)\}$$
$$+\sum_{p=2}^{|I|-1}\sum_{q(\neq p)=1}^{p-1}\{E_{pq}(t-\beta_{p|I|}) + EX_{pq}(t-\beta_{p|I|}) + EY_{pq}(t-\beta_{p|I|})$$
$$+F_{pq}(t-\beta_{p|I|})\} \leq CAP \;\; \forall t \in T, \tag{32}$$

$$C_{ij}^R = C_i^H + C_j^H + C_{ij}^T\beta_{ij} \;\; \forall i \in I, j \in I, \tag{33}$$

$$C_{ij}^L = C_i^H + C_j^H + (C_{ji}^{LL} + C_{ji}^T)\beta_{ji} + C_{ij}^{LL}\beta_{ij} \;\; \forall i \in I, j \in I, \tag{34}$$

$$FS, FF \geq 0 \text{ and integer}, \tag{35}$$

$$L_{ij}(t), B_{ij}(t), BYY_{ij}(t), E_{ij}(t), EX_{ij}(t), EY_{ij}(t), EYY_{ij}(t) \geq 0 \text{ and integer},$$
$$\forall t \in T, i \in I, j \in I, \tag{36}$$

$$S_i(t), SX_i(t), SY_i(t), SYY_i(t), D_i(t), DYY_i(t), G_i(t), GYY_i(t), N_i(t), NYY_i(t), O_i(t),$$
$$OYY_i(t), R_i(t), RYY_i(t) \geq 0 \text{ and integer}, \;\; \forall t \in T, i \in I. \tag{37}$$

The objective function (9) minimizes CMC, covering costs of owned STD/FLD fleets, repositioning/storing empties at ports, leasing containers, and port F/UF. Constraints (10) and (11) ensure empty flow conservation. Eqs. (12) and (13) confirm hinterland-returned empties are unloaded imports. Eqs. (14) and (15) illustrate that unloaded containers comprise imports from various ports h. Eqs. (16) and (17) guarantee that the empty containers at port i come from different ports h. Eqs. (18) and (19) indicate that the total number of empty containers repositioned from port i, $O_i(t)$ and $OYY_i(t)$, are distributed to different ports j. Eqs. (20) and (21) guarantee that the overall number of empty containers dispatched to shippers in the hinterland, $N_i(t)$ and $NYY_i(t)$, corresponds to the exports by owned STDs/FLDs. Eq. (22) specifies that the leased containers used from port i to port j equal the deficit of containers for exporting cargoes. Leased containers at time t compensate for the shortage of time at $t + \alpha_i$. Constraint (23) restricts empty inventory $S_i(t)$, $SX_i(t)$, and $SY_i(t)$ at each port to its respective capacity. Eqs. (24) and (25) give a flow network of owned STDs/FLDs at initial nodes. At first, the total owned containers at Nodes $(i, 1)$ equal FS and FF. Eq. (26) conserves folded/unfolded container flow between ports. The number of FLD tiers folded into one STD equals its capacity. Eq. (27) ensures that the amount of folded and unfolded containers at port i remain balanced. Constraints (28) and (29) impose restrictions on container folding/unfolding at ports. Owned ships reposition empties after loading exports at port i. Constraints (30)–(32) guarantee this relationship. They calculate a ship's spare capacity to move empties from surplus to shortage ports. Set (30) applies to Port 1 as departure, and Eq. (33) applies to the last port in RT, where $|I|$ represents the cardinality of set I (the last port of call). Eq. (31) applies to other ports. The first term represents the quantity of containers leaving port i, while the second term represents traffic from port i to port j. Eq. (33) stipulates that repositioning costs, C_{ij}^{R}, comprise handling and transport costs from port i to port j. Eq. (34) calculates leasing costs, C_{ij}^{L} by adding handling costs, returning from port j to port i, and container hire according to RT between ports. Nonlinear constraints are circumvented by evaluating the quantity of containers, whether folded or unfolded, at port i, $FU_i(t)$, without considering any folding or unfolding. Interviews have indicated that folding costs are approximately equivalent to unfolding costs.

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