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Research Article

Two-Phase Optimization Models for Liner Shipping Network Based on Hub Ports Cooperation: From the Perspective of Supply-Side Reform in China

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From the perspective of supply-side reform in China, it is hard for COSCO Shipping, a merged company with a strong shipping capacity, to abandon the container shipping market. Meanwhile, the new company could cooperate with new strategic ports along the Maritime Silk Road in liner service. Against this backdrop, this paper aims to optimize the liner shipping network (LSN) from strategic, tactical, and operational levels and help the merged shipping company adjust its operational measures according to market changes. The optimization towards different levels of decision-making process is a new research of highly practical values. Specifically, this paper created two-phase optimization models for LSN based on the selection of hub ports. In Network Assessment (NA) phase, the LSNs of two types of hub ports selected are designed and assessed on strategic and tactical levels, and the primary and secondary routes are identified; in Network Operation (NO) phase, the "path-based flow" formulations are proposed from the operational level, considering operational measures including demand rejection and flow integration. The models in both phases are mixed-integer linear programming (MILP), but are solved by different tools: CPLEX for the NA phase models and the Genetic Algorithm (GA) for the NO phase models due to the computational complexity of the latter problem. Then, a computational experiment is performed on the LSN of COSCO Shipping on the Persian Gulf trade lane. The results have proved the effectiveness of the methodology and inspired important countermeasures for the merged shipping company.

1. Introduction

The global demand for container shipping had been rapidly increasing from the birth of the containership in the 1950s to the outbreak of the subprime crisis [1]. Due to the limited shipbuilding capacity, however, the container shipping suffered from a long-lasting capacity bottleneck, which was not resolved until about 1995. Since then, expansion of shipping capacity has grown explosively and maintained a continuous lead over the demand increase. After 2004, the shipping capacity utilization rate, i.e., ship loading rate, exhibited an obvious decline, heralding the dawn of the "oversupply" period in the container shipping [2]. Since the global recession that began in 2008, the demand growth of shipping industry has slowed and fallen more in line with GDP growth. In 2019, the worrying trend of the falling trade-to-GDP ratio still continues. Both the US-China trade war and the global sulfur limit implemented by International Maritime Organization (IMO), the regulatory authority for international shipping, put forward potential threats to the demand side of shipping industry [3]. It is predicted that shipping oversupply will persist and be an even greater cause for concern [4].

In order to deal with the oversupply issue, governments and shipping industry have been making efforts to conduct supply-side reform. The supply-side reform consists of a series of parallel measures and regulations, including annual capacity limits and mergers of shipping companies. The

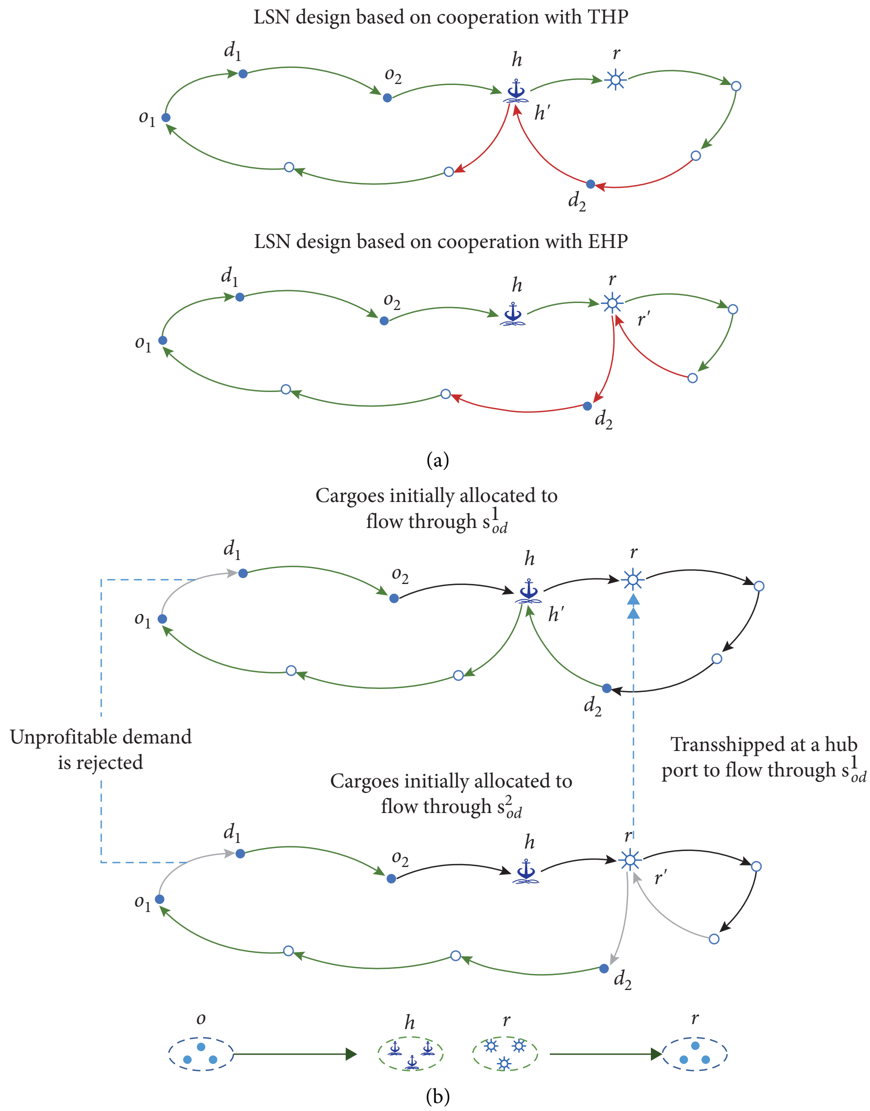


Figure 1: Two-phase decision-making process for merged shipping company. (a) The LSN design problem in the NA phase and (b) the LSN operation problem in the NO phase.

most intuitive way is to directly control the growth of freight capacity. For example, the Chinese government is imposing a gradually stringently macrocontrol to maritime freight capacity. Currently, any expansion of fleet that transport bulk liquid hazardous goods need to be scrutinized [5]. It can be expected that the control of containership capacity will be put forward in the upcoming future in order to eliminate the gap between supply and demand of maritime industry.

In comparison with the annual capacity limit that seems in lack of mature practice, mergers and alliances is an obvious trend in recent years leading to the concentration of shipping capacity. There have been several successful cases of mergers in the maritime industry. The largest five carriers handled 27% of all TEUs in 1996, 46% in 2008, and 64% in 2017 [6]. A typical example is the merger between China Ocean Shipping Company (COSCO) and China Shipping Company (CSCL) in 2016, marking a major move in the supply-side reform of China's shipping industry [7]. The two leading shipping companies integrated into COSCO Shipping Group (COSCO Shipping), which has become the world's 3rd largest shipping company in 2019 [8].

The rationale of the COSCO/CSCL merger is entirely sound as they both have designed many similar services, and the unnecessary competition has deteriorated their financial performance. Besides eliminating competition, there are more benefits awaited the shipping companies through optimizing their LSNs after mergers, which is investigated in this paper. In practice, after mergers, the LSNs of the acquired shipping companies need to firstly go through strict assessment, then considering adjusting the services. The Network Assessment (NA) phase and Network Operation (NO) phase differ greatly in the content and process of the

Table 1: Notations of model in NA phase.

Sets	
N	Set of all nodes in the LSNs
H	Set of all traditional hub ports (THP)
R	Set of all emerging hub ports (EHP)
O	Set of all origin ports of demands
D	Set of all destination ports of demands
V	Set of all available legs in the LSNs
Parameters	
π	Capacity of any deployed containership
$c_{i_1 i_2}$	Voyage expense of operating on leg $(i1, i2) \in V$
$w_{i_1 i_2}$	Transit time of operating on leg $(i1, i2) \in V$
Ω	Maximum containership capacity for a voyage circle controlled by the government
Qod	Quantity of demand between origin port $o \in O \subseteq N$ and destination port $d \in D \subseteq N$
eod	Freight rate of transporting unit demand between origin port $o \in O \subseteq N$ and destination port $\mathrm{d} \in D \subseteq N$
E	Expected total revenue, which can be calculated as $\sum_{o \in O} \sum_{d \in D} e_{od} Q_{od}$
W	Fixed transit time for the total legs in a voyage cycle
Decision variables	
$y_{i_1 i_2}$	(Binary) 1 iff the leg $(i1, i2)$ exists
$f_{i_1 i_2}$	The number of containers to be transported on leg $(i1, i2) \in V$
z	The number of deployed containerships

decision-making of the shipping companies [9]. Both phases are necessary to be considered for merged shipping companies to obtain sustained competitiveness [10].

In this paper, two-phase optimization models are proposed to investigate the decision-making process in NA and NO phases, aimed at maximizing the actual profits of a shipping company in the context of supply-side reform, for the LSN based on strategic ports, investigating the decision-making process in NA and NO phases. Various factors are considered to better reflect the NA phase and NO phase in practice, such as the cooperation with different hub ports, the transshipment of cargoes, the rejection of unprofitable demand, and the fluctuation of demands and freight rates.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature and summarizes the contributions of this study; Section 3 presents a clear description of the problem; Section 4 establishes the two-phase optimization model; Section 5 details the GA-based algorithm for the LSN in NO phase, alongside CPLEX, enabling the solutions for LSNs in NA phase; Section 6 carries out a computational experiment on the LSN of COSCO Shipping; Section 7 wraps up this paper with some meaningful conclusions.

2. Literature Review

There are three decision-making levels for the shipping companies to design LSN: strategic, tactical, and operational [11]. At the strategic level, the shipping companies often make long-term decisions that may cover a planning horizon of up to 30 years. Containership deployment is concerned with the structure (size) and scale (number) of containerships [12, 13]. Another strategic decision is route design. The aim of route design is to determine which ports the containerships should visit and in what order [14]. Strategic decisions clearly affect the decision-making at the tactical levels by defining the boundaries for these decisions. At the tactical level, the focus lies in frequency determination [15], sailing speed optimization [16, 17], and schedule design [18, 19]. Tactical level decisions are made every three to six months in view of changing demand for container shipping [20, 21]. At the operational level, the shipping companies determine whether to accept or reject freights [22], how to flow accepted freights [23], and how to reroute or reschedule containerships to cope with unexpected market changes [24]. There is some interplay between the decisions made at the three different levels [25].

Most existing literature on the optimization of the LSN is devoted to the strategic and tactical levels. Wang and Meng [13] give a literature survey on liner fleet deployment. Ronen [26] pioneered the study on ship deployment and route design in 1983. Later, Rana and Vickson [27], Fagerholt [28], Christiansen et al. [29], Gelareh and Pisinger [30], and Sheng et al. [31] deepened the research based on these strategic decisions. Meng et al. [32] and Dulebenets et al. [33] reviewed the past research on container scheduling problems. Dulebenets [34], Wang et al. [35], and Alharbi et al. [18] studied the ship schedule problems considering port time windows. Because of the high costs of containership deployment and route design, and the complexity of the scheduling problems, the latest literature mainly applies operations research methods to address the strategic and tactical problems in LSN design. In recent years, much attention has been paid to the operational optimization of the LSN. Some scholars highlighted freights booking. In essence, the demand for container shipping bears on the decision-making of all stakeholders, including the ports and the shipping companies. For instance, Brouer et al. [36], Song and Dong [37], and Daniel et al. [38] presented the freights booking decisions generated from LP models where the freight flows are treated as a continuous decision variable. Liu et al. [39] and Wang et al. [40] pointed out the possibility of increasing the port handling rates while optimizing ship fuel cost at the same time. The cooperation

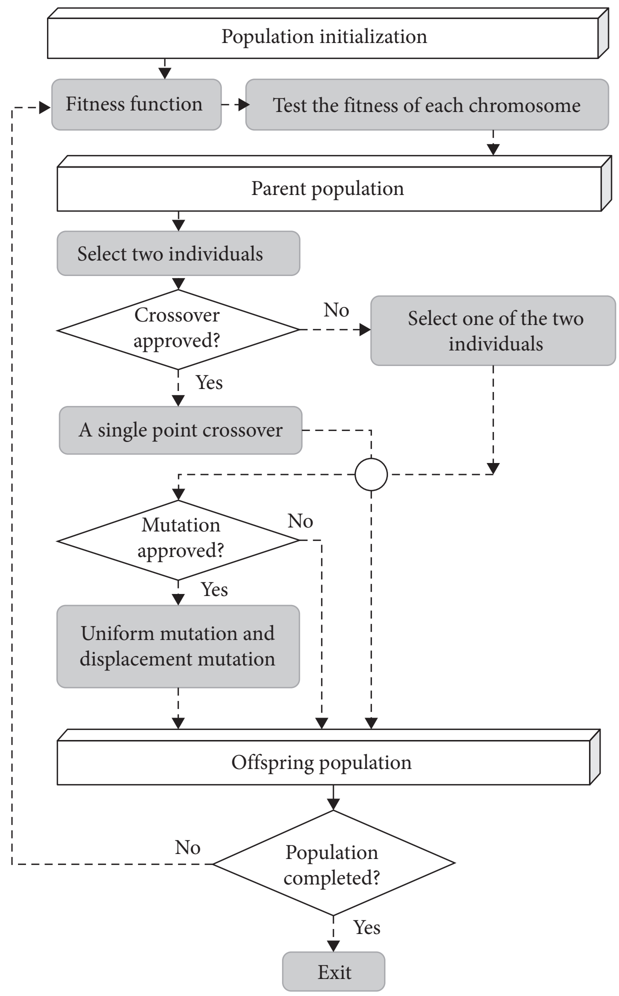


Figure 2: Flowchart of the proposed GA-based algorithm to model (III).

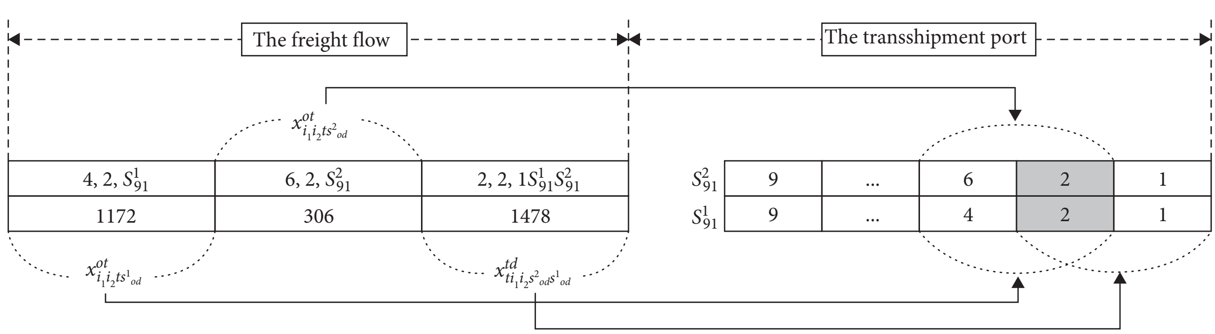


Figure 3: A typical solution to model (III).

between shipping companies and port operators was also investigated by Venturini et al. [41] and Dulebenets [42] from multiobjective perspectives. For some other scholars, containership rerouting was regarded as a special problem of operational optimization [43]. The LSN design problem is NP-hard with computationally challenge [44], and we cannot expect to find a polynomial-time algorithm that will produce the optimal solution for a general LSN design problem unless P=NP. Considering that the LSN design problem is already NP-hard, efficient heuristic-rules-based methods might be expected to address large-scale realistic systems [45].

From the above discussion, it is clear that the strategic and tactical decisions are often an input to the operational optimization. The idea of combining different levels of decision-making has been absorbed in some studies in recent years, known as two-phase optimization. By generating the set of routes firstly, the container flows can be optimized based on the given set of routes in the second phase [46, 47]. The operational optimization of the LSN can also be viewed as the fine-tuning and correction of the strategic and tactical solutions [48]. Despite the aforementioned advancements in the research on the LSN design problem, there are still some practically significant issues that have seldom been addressed. For example, liner shipping consolidation through mergers and the macrocontrol of excessive new capacity are regarded as key challenges for maritime industry in 2019; however, it has been ignored by researchers so far [49].

This research fills in the gap in the existing literature and makes contributions to the research in LSN design problem as follows. Firstly, we investigate the LSN design problem for shipping companies under the context of supply-side reform. Various measures of supply-side reform are considered in this paper, including the macrocontrol of capacity and the mergers of shipping companies. The decision-making process is divided into NA phase and NO phase, and two-phase optimization models for the LSN are developed accordingly. Secondly, we look for alternative solutions to the LSN design problem in the NO phase with a GA-based algorithm. The proposed method can efficiently solve the "path-based flow" formulations. Thirdly, this paper gives out several countermeasures of shipping companies from the perspective of supply-side reform in China, e.g., the selection of hub ports, demand rejection, and the idea of flow integration. In addition, the scenario analyses reveal how shipping companies can flexibly adjust their operational measures according to the actual market indicators such as demand and freight rates.

3. Problem Description

We consider the LSN optimization for a shipping company in the context of supply-side reform, typically a merger or acquisition. NA and NO phases after a merger are analyzed: selecting the most profitable route in the NA phase from all the similar preset routes that have been designed by different acquired shipping companies, and figuring out the optimal plan of flowing cargoes in the NO phase according to the actual shipping market. The objectives of both phases are to maximize profits. Detailed information about the two phases is stated in Section 3.1 and Section 3.2, respectively.

The elements of LSN are defined as follows to avoid ambiguity:

(1) Port calls: a typical liner shipping route usually contains at least several fixed ports calls, thus also named as multiport calling (MPC) service [50].

(2) Hub ports: when operating along a liner service, the containerships are allowed to call twice at hub ports, but only once at any other ports. As commonly observed in practice, each route is limited to one single hub port. The shipping companies can cooperate with different hub ports, which can be classified as traditional hub ports (THPs) and emerging hub ports (EHPs). In addition, hub ports are able to transship cargoes due to better facilities.

(3) Routes: the route in the LSN may have 10–20 legs, where a leg is a directed arc between two consecutive ports [51, 52].

(4) Cargo flows: cargo flow refers to the move of cargoes on a leg. A flow path is the directed path consisted of all the legs between the origin port and the destination port.

(5) Demands: there are several pairs of origin and destination (O-D pairs) of cargoes along a route, generating shipping demands. The market changes are represented by the variation of demands and freight rates for container shipping [53]. Shipping companies can hardly control the freight rates (e.g., CCFI and SCFI). The only thing they can do regarding the shipping market is to decide whether satisfy or reject the demands, which can be called as "cherry-picking" [54].

3.1. The LSN Design Problem in NA Phase. Suppose two shipping companies, represented by A and B, respectively, are merged into a new shipping company C. In the NA phase, there are already similar routes established by the acquired shipping companies A and B. Such similar preset routes may be initiatively designed to satisfy the demand in the same regions, which leads to unnecessary competition. Despite the similarities, the selection of hub ports contributes to the differences among the routes. For instance, A has established a cooperative relationship with traditional hub ports (THP); i.e., the containerships operated by A are allowed to call twice at the THP. However, B noticed that the shipping demands generated from Emerging Hub Ports (EHP) are growing rapidly, thus is more willing to cooperate with EHP [55]. The differences of the preset routes result in different profits. Therefore, for shipping company C that can either cooperate with THP or EHP, it is necessary to assess the profitability of the preset routes in order to make adjustment plans.

The assessment is based on the prediction regarding the quantities of demands Q_{od} and freight rates e_{od} in the next 10–30 years, according to experts' knowledge of the market and the development of maritime policies. For any cooperation strategy with hub ports, the decision-maker can construct a model with predicted demands input to design the corresponding LSN. The results of the assessment indicate cooperating with which types of hub ports (THP or EHP) are more likely to be profitable. Here, for simplicity, we define the more profitable route as primary route and the less profitable one as secondary route. Then, shipping company C should adjust the container flows to the primary routes, as the thought of aggregating flows on fewer routes in Krogsgaard et al. [56]. In other words, the secondary route will no longer need to flow cargoes to save operation cost.

3.2. The LSN Operation Problem in NO Phase. The assessment results in the NA phase based on predicted demand give out a rough principle that more cargoes should flow on the primary route. In the NO phase, in order to start operation in practice, shipping company C needs to depict more detailed plans on how to adjust cargo flows, which involve how to pick up, unload, and transship containers at any port of call according to the actual market situation.

As shown in Figure 1(a), two similar routes have been designed according to different preferences of hub ports and named as primary route and secondary route based on predicted demands in the NA phase, respectively. The different legs of the two routes are painted in red. Here, the LSNs can be described by a directed graph $G=(N,V)$ containing n nodes $i\in N=\{1, 2, \ldots, n\}$ and v legs $v\in V=\{1, 2, \ldots, v\}$. The set of origin ports of shipping demand is represented by O, and the set of destination port is represented by D. For any THP h or EHP r that is called twice in the designed LSN, theoretical copies, i.e., h' and r', are used to differentiate two calls to one hub port. The cost and the transit time associated with the leg (h, h') or (r, r') are 0. We represent the set of THPs by H and the set of EHPs by R.

The flow path of any shipping demand from origin port o to destination port d on the primary route and the secondary route can be represented by $s^1_{o\,d}$ and $s^2_{o\,d}$, respectively. If $s^1_{o\,d}$ and $s^2_{o\,d}$ are the same, e.g., the shipping demand (o_1, d_1) in Figure 1(b), it does not matter whether the flow path is selected as $s^1_{o\,d}$ or $s^2_{o\,d}$. However, if $s^1_{o\,d}$ and $s^2_{o\,d}$ are different, e.g., the shipping demand (o_2, d_2) in Figure 1(b), the part of cargo flow that has selected $s^2_{o\,d}$ should be adjusted to $s^1_{o\,d}$. Obviously, the difference between $s^1_{o\,d}$ and $s^2_{o\,d}$ is derived from the selection of hub ports, i.e., THP h or EHP r. Since the hub ports have better conditions for transshipping, a feasible solution to adjust the flow path is that any cargo flow transported in s^2_{od} should transship at a hub port to s^1_{od}. By adopting the idea of "flow integration," the shipping company C can aggregate the cargo flows to more profitable route.

In NO phase, the decision-making is based on actual demands and freight rates, which may have a deviation ΔQ_{od} and Δe_{od} from prediction. It should be noticed that the demands and freight rates are time-varying; hence, it is necessary to make timely and pertinent adjustment to the LSNs in order to achieve low-cost operation. In addition, when operating the LSNs, shipping companies prefer to reject the unprofitable cargoes if allowed [57], e.g., the shipping demand (o_1, d_1) in Figure 1(b). In this paper, the fluctuation of market indicators is specifically analyzed in Section 6. "Flow integration" and "demand rejection" are reflected in the model in Section 4 with an aim of maximizing profits, making the operation of LSNs more flexible. In conclusion, for each O-D pair, shipping company C in the NO phase needs to figure out how many containers to be transported through $s^1_{o\,d}$ and $s^2_{o\,d}$ and how many containers to be rejected.

4. Mathematical Model

The assumptions of the models are listed here as follows:

(1) Without considering the impact of natural disasters and local wars on the LSN, any demand between an O-D port pair is a long-standing issue that changes with the global trade.
(2) Without considering the difference between types of containerships, the voyage expense incurred by containership deployment is fixed, and all containerships sail at the agreed speed [58].
(3) There is no limit on the loading/unloading capacities of all ports, that is, any port can handle the maximum containership capacity. The terminal handling charges are fixed on each port, but vary among all ports [59].
(4) The emission regulations of MARPOL-VI and EU-ETS on ports and containerships are not considered, as their impacts are restricted to certain areas and are negligible for long-haul liner services [60].

4.1. Formulation for LSN Design Problem in NA Phase. The LSN design problem in the NA phase based on hub ports selected as THPs is formulated as Model (I). The notations used the model in the NA phase are shown in Table 1. Here, we consider that the government may control the fleet expansion in order to resolve oversupply in maritime industry. Hence, we introduce a parameter Ω to represent the possible maximum limit of containership capacity that can be deployed for a voyage circle imposed by the government.

Having defined the notations, we have Model (I) as follows:

$$\min Z_1 = \sum_{i_1\in N}\sum_{i_2\in N} c_{i_1 i_2} y_{i_1 i_2} - E, \tag{1}$$

$$\text{s.t.} \sum_{i_2\in N} y_{i_1 i_2} - 1 = 0, \quad i_1 \in \frac{N}{H}, \tag{2}$$

$$\sum_{i_2\in N} y_{i_2 i_1} - 1 = 0, \quad i_1 \in \frac{N}{H}, \tag{3}$$

$$1 - \sum_{i\in N} y_{hi} \leq 0, \quad h \in H \subset N, \tag{4}$$

$$1 - \sum_{i\in N} y_{ih} \leq 0, \quad h \in H \subset N, \tag{5}$$

$$\sum_{i\in N} y_{hi} - 2 \leq 0, \quad h \in H \subset N, \tag{6}$$

$$\sum_{i\in N} y_{ih} - 2 \leq 0, \quad h \in H \subset N, \tag{7}$$

$$\sum_{i\in N} y_{ih} = \sum_{i\in N} y_{hi}, \quad h \in H \subset N, \tag{8}$$

$$\sum_{o\in N} Q_{oi_1} - \sum_{d\in N} Q_{i_1 d} = \sum_{i_2\in N} f_{i_2 i_1} - \sum_{i_2\in N} f_{i_1 i_2}, \quad i_1 \in N, \tag{9}$$

$$\sum_{d\in D} Q_{od} - \sum_{i_1\in N} f_{oi_1} \leq 0, \quad o \in O, \tag{10}$$

$$\sum_{o\in O} Q_{od} - \sum_{i_1\in N} f_{i_1 d} \leq 0, \quad d \in D, \tag{11}$$

$$\sum_{i_1\in N}\sum_{i_2\in N} w_{i_1 i_2} y_{i_1 i_2} - W \leq 0, \tag{12}$$

$$f_{i_1 i_2} - y_{i_1 i_2}\Omega \leq 0, \quad i_1 \in N, i_2 \in N, \tag{13}$$

$$f_{i_1 i_2} - z\pi \leq 0, \quad i_1 \in N, i_2 \in N, \tag{14}$$

$$f_{i_1 i_2} \in Z^+, \quad i_1 \in N, i_2 \in N, \tag{15}$$

$$y_{i_1 i_2} \in \{0,1\}, \quad i_1 \in N, i_2 \in N. \tag{16}$$

$$z \in Z^+. \tag{17}$$

Objective function (1) maximizes the predicted profits of the LSN based on the THPs. Constraints (2) and (3) specify that the containership is allowed to call only once at all ports other than the THPs, that is, these ports have only one incoming leg and one outgoing leg. Constrains (4)–(7) can be combined to define that the number of incoming legs and outgoing legs for each THP is either one or two. Constraints (8) guarantee that the number of legs that enter a THP is equal to the number of legs that leaves a THP. Constraints (9) guarantee that the difference of the cargo flows between incoming legs and outgoing legs for every port is equal to the quantity of demand surplus/deficit. This is ensured by. Constraints (10) require that the flows on the outgoing leg satisfy the total quantity of the demand from any port $o \in O$ as an origin port, and as indicated for any port $d \in D$ as a destination port by constraints (11). Constraint (12) stipulates that the whole transit time for all legs in the LSN must obey the fixed transit time. Constraint (13) states that the flows on every leg should not exceed the maximum containership capacity controlled by the government. Constraint (14) rules that the flows on the leg must be carried by enough containerships. Constraints (15)–(17) define the domain of the decision variables.

Unlike the set of the THPs in constraints (4)–(7), the number of incoming legs and outgoing legs for the EHP is determined by

$$\begin{aligned} &1 - \sum_{i\in N} y_{ri} \leq 0, && r \in R \subset N, \\ &1 - \sum_{i\in N} y_{ir} \leq 0, && r \in R \subset N, \\ &\sum_{i\in N} y_{ri} - 2 \leq 0, && r \in R \subset N, \\ &\sum_{i\in N} y_{ir} - 2 \leq 0, && r \in R \subset N, \end{aligned} \tag{18}$$

$$\sum_{i\in N} y_{ih} = \sum_{i\in N} y_{hi}, \quad r \in R \subset N. \tag{19}$$

The LSN design problem in the NA phase based on hub ports which are the EHPs is given as Model (II).

$$\begin{aligned} \min \quad & Z_2 = \sum_{i_1\in N}\sum_{i_2\in N} c_{i_1 i_2} y_{i_1 i_2} - E, \\ \text{s.t.} \quad & (2), (3), (9) - (22). \end{aligned} \tag{20}$$

4.2. Formulation for LSN Operation Problem in NO Phase. The LSN design problem in the NO phase to determine the optimal cargo flows is formulated as Model (III). As defined in Section 3, the flow path of demand generated from an O-D pair on the primary route is $s^1_{o\,d}$, while the flow path on the secondary route is $s^2_{o\,d}$. Besides, we use $t \in (N/o)$ to represent the transshipment port. Since $s^1_{o\,d}$ is predicted as the more profitable flow path, any containers that initially flow on $s^2_{o\,d}$ should be integrated into $s^1_{o\,d}$ at transshipment port t.

For any path $s^k_{o\,d}$, $k \in \{1,2\}$, we have

$$\begin{aligned} &\left(i, t, s^k_{o\,d}\right) \in \begin{cases} L, & i_1 \text{ falls on the } s^k_{o\,d} \text{ containing } t; \\ \varnothing, & i_1 \text{ does not fall on the } s^k_{o\,d} \text{ containing } t, \end{cases} \\ &\left(i_1, i_2, t, s^k_{o\,d}\right) \in \begin{cases} K^1, & (i_1, i_2) \text{ comes before } t \text{ on the } s^k_{o\,d}; \\ \varnothing, & (i_1, i_2) \text{ does not come before } t \text{ on the } s^k_{o\,d}, \end{cases} \\ &\left(t, i_1, i_2, s^k_{o\,d}\right) \in \begin{cases} K^2, & (i_1, i_2) \text{ comes after } t \text{ on the } s^k_{o\,d}; \\ \varnothing, & (i_1, i_2) \text{ does not come after } t \text{ on the } s^k_{o\,d}. \end{cases} \end{aligned} \tag{21}$$

In Model (III), we define c_i as the loading/unloading cost of port $i \in N$. The decision variables in the NO phase are listed as follows:

(1) $x^{ot}_{i_1 i_2 t s^1_{o\,d}}$: the cargo flow on any leg (i_1, i_2) before the transshipment port t on $s^1_{o\,d}$ between origin port o and destination port d

(2) $x^{ot}_{i_1 i_2 t s^2_{od}}$: the cargo flow on any leg (i_1, i_2) before the transshipment port t on $s^2_{o\,d}$ between origin port o and destination port d

(3) $x^{t\,d}_{t i_1 i_2 s^2_{o\,d} s^1_{o\,d}}$: the cargo flow on any leg (i_1, i_2) after the transshipment port t on $s^1_{o\,d}$, where the flow to the transshipment port t is transported on $s^2_{o\,d}$

$$
\begin{aligned}
\min \quad Z_3 = {} & \sum_{o\in N}\sum_{d\in N}\sum_{i_1\in N}\sum_{i_2\in N}\sum_{t\in N}\left(c_{i_1}+c_{i_2}\right)\left(x^{ot}_{i_1 i_2 t s^1_{o\,d}}+x^{ot}_{i_1 i_2 t s^2_{o\,d}}\right)+\sum_{o\in N}\sum_{d\in N}\sum_{i_1\in N}\sum_{i_2\in N}\sum_{t\in N}\left(c_{i_1}+c_{i_2}\right)x^{t\,d}_{t i_1 i_2 s^2_{o\,d} s^1_{o\,d}} \\
& -\sum_{o\in N}\sum_{d\in N}\sum_{i_1\in N}\sum_{t\in N}\left(e_{o\,d}+\Delta e_{o\,d}\right)\left(x^{ot}_{o i_1 t s^1_{o\,d}}+x^{ot}_{o i_1 t s^2_{o\,d}}\right),
\end{aligned}
\tag{22}
$$

$$
\begin{aligned}
\text{s.t.} \quad & \left(x^{ot}_{o i_1 t s^1_{o\,d}}+x^{ot}_{o i_1 t s^2_{o\,d}}\right)-\left(Q_{o\,d}+\Delta Q_{o\,d}\right) \\
& \leq 0, \quad o\in N, d\in N, i_1\in \frac{N}{o}, t\in\frac{N}{o}, \left(i_1, t, s^k_{o\,d}\right)\in L, k\in\{1,2\},
\end{aligned}
\tag{23}
$$

$$
\sum_{o\in N}\sum_{d\in N}\sum_{t\in N}\left(x^{ot}_{i_1 i_2 t s^1_{o\,d}}+x^{ot}_{i_1 i_2 t s^2_{o\,d}}\right)-\Omega\leq 0, \quad i_1\in\frac{N}{t}, i_2\in N, \left(i_1, i_2, t, s^k_{o\,d}\right)\in K^1, k\in\{1,2\},
\tag{24}
$$

$$
\sum_{o\in N}\sum_{d\in N}\sum_{t\in N} x^{t\,d}_{t i_1 i_2 s^2_{o\,d} s^1_{o\,d}}-\Omega\leq 0, \quad i_1\in\frac{N}{t}, i_2\in N, \left(t, i_1, i_2, s^1_{o\,d}\right)\in K^2,
\tag{25}
$$

$$
\sum_{i_2\in N} x^{ot}_{i_2 i_1 t s^1_{o\,d}}-\sum_{i_2\in N} x^{ot}_{i_1 i_2 t s^1_{o\,d}}=0, \quad o\in N, d\in N, i_1\in\frac{N}{t}, t\in\frac{N}{d}, \left(i_1, t, s^1_{o\,d}\right)\in L,
\tag{26}
$$

$$
\sum_{i_2\in N} x^{ot}_{i_2 i_1 t s^2_{o\,d}}-\sum_{i_2\in N} x^{ot}_{i_1 i_2 t s^2_{o\,d}}=0, \quad o\in N, d\in N, i_1\in\frac{N}{t}, t\in\frac{N}{d}, \left(i_1, t, s^2_{o\,d}\right)\in L,
\tag{27}
$$

$$
\sum_{i_2\in N} x^{t\,d}_{t i_2 i_1 s^2_{o\,d} s^1_{o\,d}}-\sum_{i_2\in N} x^{t\,d}_{t i_1 i_2 s^2_{o\,d} s^1_{o\,d}}=0, \quad o\in N, d\in N, i_1\in\frac{N}{\{t,d\}}, t\in\frac{N}{d}, \left(i_1, t, s^1_{o\,d}\right)\in L,
\tag{28}
$$

$$
\sum_{i_1\in N} x^{ot}_{i_1 t t s^1_{o\,d}}+\sum_{i_1\in N} x^{ot}_{i_1 t t s^2_{o\,d}}-\sum_{i_1\in N} x^{t\,d}_{t t i_1 s^2_{o\,d} s^1_{o\,d}}=0, \quad t\in\frac{N}{\{o,d\}}, \left(i_1, t, s^k_{o\,d}\right)\in L, k\in\{1,2\},
\tag{29}
$$

$$
x^{ot}_{i_1 i_2 t s^1_{o\,d}}\in\left\{0, Z^+\right\}, \quad o\in N, d\in N, i_1\in\frac{N}{t}, i_2\in N, t\in\frac{N}{o}, \left(i_1, i_2, t, s^1_{o\,d}\right)\in K^1,
\tag{30}
$$

$$
x^{ot}_{i_1 i_2 t s^2_{o\,d}}\in\left\{0, Z^+\right\}, \quad o\in N, d\in N, i_1\in\frac{N}{t}, i_2\in N, t\in\frac{N}{o}, \left(i_1, i_2, t, s^2_{o\,d}\right)\in K^1,
\tag{31}
$$

$$
x^{t\,d}_{t i_1 i_2 s^2_{o\,d} s^1_{o\,d}}\in\left\{0, Z^+\right\}, \quad o\in N, d\in N, i_1\in\frac{N}{d}, i_2\in N, t\in\frac{N}{o}, \left(t, i_1, i_2, s^1_{o\,d}\right)\in K^2.
\tag{32}
$$

Objective function (22) maximizes the actual profits of the shipping company by demands rejection and flow integration, i.e., minimizes the difference between the operation costs and the temporal revenues. The operation costs in the NO phase refer to the total loading/unloading cost along the design path, which is incurred once at the origin and destination ports and twice at the ports of call. Similar to related studies with two-phase optimization, the operation costs in the NO phase only consist of the variable costs related to cargo flows, excluding the voyage expenses considered in the NA phase because the voyage expense of LSN is fixed once the LSN is established. Constraints (23) require that the accepted demand, i.e., the total cargo flow on the outgoing leg for the origin port (including cargo flows on different flow paths $s^1_{o\,d}$ and $s^2_{o\,d}$), should not exceed the overall demand of each O-D port pair. Constraints (24) and (25) stipulate that the flow on any leg should not surpass the maximum limit of containership capacity for a voyage circle. Constraints (26)–(29) ensure the balance between the flow on incoming legs and outgoing legs for any port along the

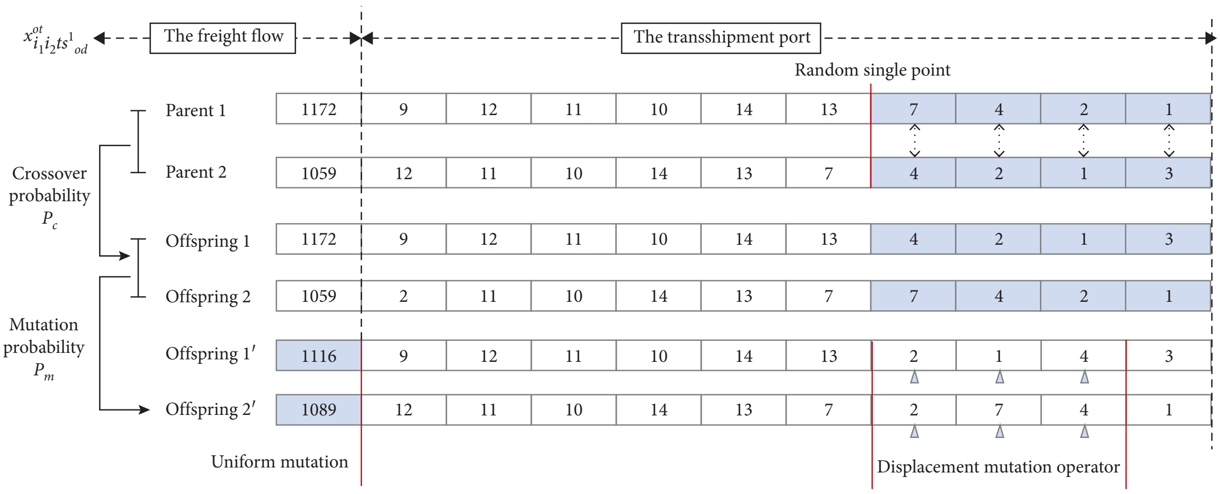
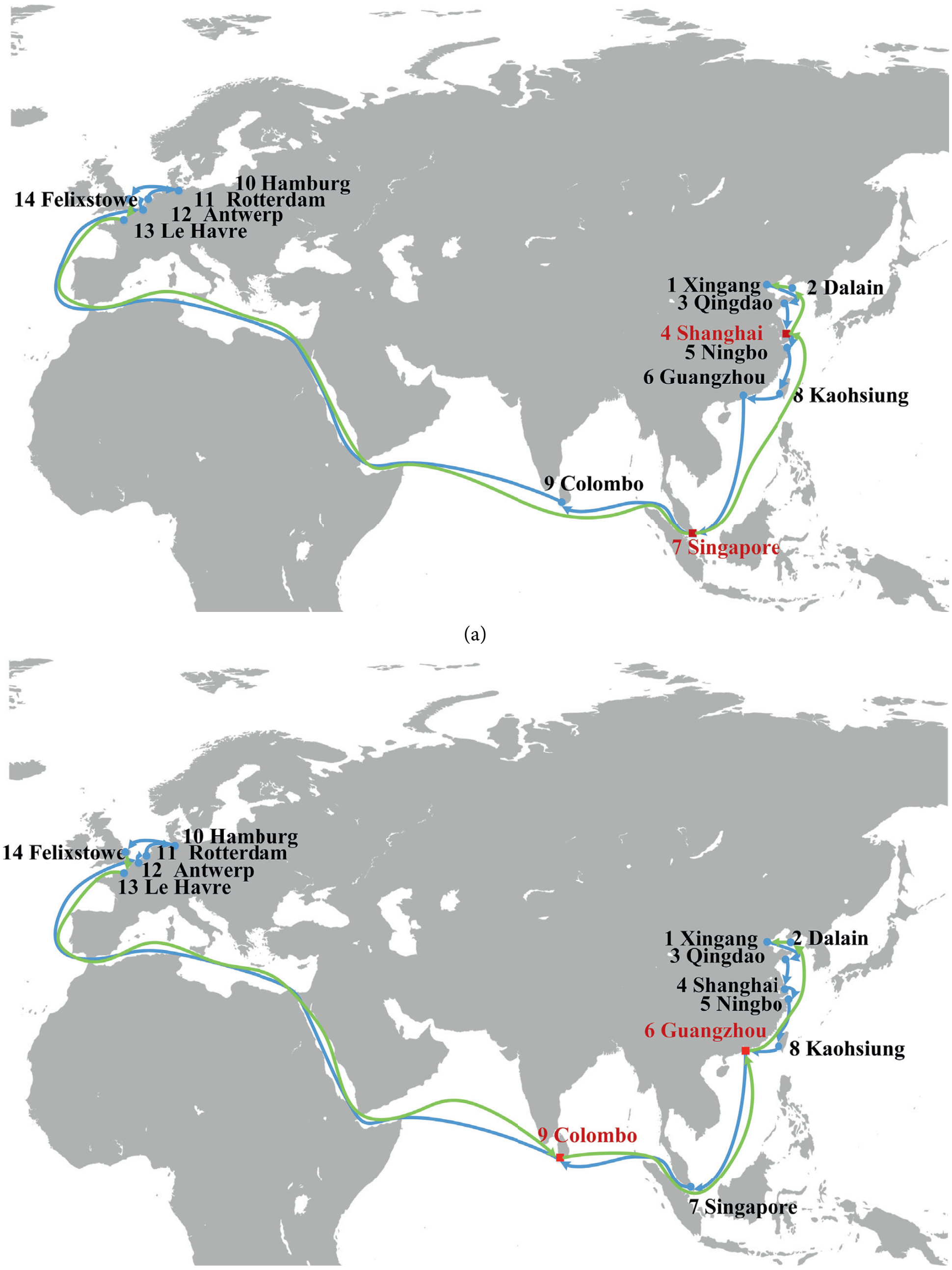


Figure 4: An example of crossover and mutation.

Table 2: The test results of 30 different $\{W, \Omega\}$ combinations.

	W (DAY)	Ω (TEU)	$-Z_1$ (USD)	Gap (%)	Time (s)	$-Z_2$ (USD)	Gap (%)	Time (s)
1	**83**	**354740**	**−29441**	**100**	**4.52**	**−4627**	**100**	**7.84**
2	**86**	**367562**	**−16619**	**100**	**5.47**	**1823446452**	**0.08**	**2.66**
3	**89**	**380384**	**−3797**	**100**	**6.08**	1823446452	0.07	3.08
4	**92**	**393205**	**1817199741**	**0.16**	**2.55**	1837997487	0.32	2.95
5	95	406027	1817209621	0.08	1.42	1838152024	0.08	2.66
6	98	418849	1817209621	0.17	3.31	1838286035	0.09	2.84
7	101	431671	1817209621	0.08	1.70	1838393254	0.06	2.78
8	104	444493	1827488337	0.16	2.58	1841772518	0.05	2.39
9	107	457315	1827478457	0.12	2.33	1842149323	0.11	2.36
10	110	470137	1827488337	0.10	1.53	1842149323	0.09	2.94
11	113	482959	1828105883	0.42	2.34	1842149323	0.11	2.72
12	116	495781	1828105883	0.09	1.89	1842149323	0.06	3.16
13	119	508603	1828105883	0.46	2.31	1842149323	0.01	2.84
14	122	521425	1828105883	0.11	1.52	1842149323	0.07	2.97
15	125	534247	1828105883	0.14	3.81	1842149323	0.11	3.00
16	128	547068	1828105883	0.04	3.05	1842149323	0.10	3.70
17	131	559890	1828105883	0.05	3.22	1842149323	0.35	2.86
18	134	572712	1828105883	0.01	3.34	1842149323	0.17	3.53
19	137	585534	1828105883	0.13	4.30	1845244453	0.14	2.38
20	140	598356	1828105883	0.08	3.56	1845244453	0.04	2.45
21	143	611178	1831418092	0.41	2.30	1847951008	0.13	4.00
22	146	624000	1831418092	0.05	2.58	1847951008	0.32	2.89
23	149	636822	1836229052	0.37	2.78	**1859269034**	**0.11**	**1.09**
24	152	649644	1836229052	0.18	4.45	**1859269034**	**0.05**	**1.81**
25	**155**	**662466**	**1851381648**	**0.06**	**2.50**	**1859269034**	**0.05**	**1.16**
26	**158**	**675288**	**1851381648**	**0.22**	**1.33**	**1859269034**	**0.06**	**1.11**
27	**161**	**688110**	**1851381648**	**0.11**	**2.03**	**1859269034**	**0.13**	**0.94**
28	**164**	**700932**	**1851381648**	**0.26**	**1.03**	**1859269034**	**0.09**	**0.91**
29	**167**	**713753**	**1851381648**	**0.08**	**1.03**	**1859269034**	**0.07**	**1.86**
30	**170**	**726575**	**1851381648**	**0.10**	**2.00**	**1859269034**	**0.15**	**0.83**



(a)

(b)

FIGURE 5: The results of LSNs (G^1 and G^2) in NA phase at $\{W = 155,\ \Omega = 662466\}$.

designed paths, including any transshipment port. In other words, they make sure that all flows unloaded at the transshipment port from s_{od}^2 are transported through s_{od}^1. Constraints (30)–(32) state the domain of the decision variables.

5. Solution Approach

The resulting models (I)~(III) are all MILP problems. Models (I)~(II) will be solved by the standard solver such as CPLEX [61], but we cannot guarantee that CPLEX would find the optimal solution for Model (III) because of the 5- and 6-index formulation required to represent the flow of every path in NO phase. Consequently, we propose using a GA-based algorithm because of several reasons: unlike other metaheuristics such as simulated annealing [62] and tabu search [63] that work with a single solution, GA deals with a population of solutions, and the GA has been successfully applied to previous applications involving LSN design problems [64, 65].

The proposed solution approach can be stated as follows: CPLEX explores the space of containership deployment and route design and finds feasible solutions. From every solution, a valid LSN configuration is derived. Once a valid

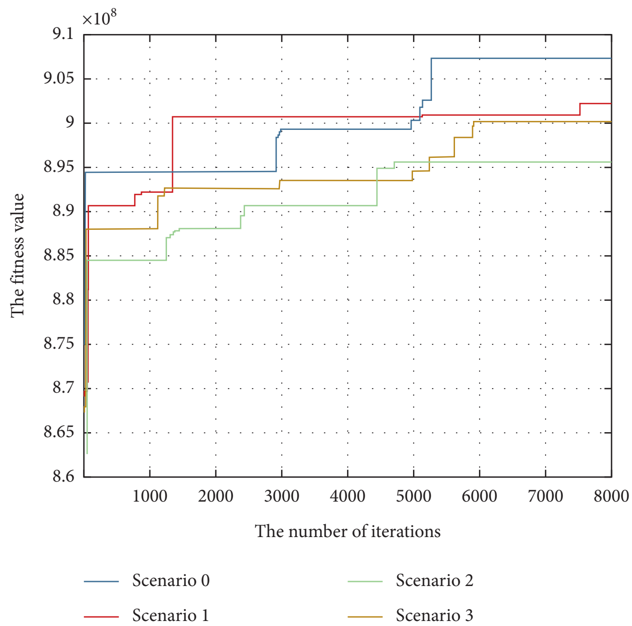


Figure 6: The convergence of LSN in NO phase (G^3).

Table 3: The results of LSN in NO phase (G^3).

G^3(%)	$o \longrightarrow d$	ΔQ_{od} (%)	Δe_{od} (%)	G^3 (%)	$o \longrightarrow d$	ΔQ_{od} (%)	Δe_{od} (%)	G^3 (%)	$o \longrightarrow d$	ΔQ_{od} (%)	Δe_{od} (%)
100	**$1 \longrightarrow 9$**	1	−14	**91.91**	**$7 \longrightarrow 11$**	4	−7	**83.23**	**$4 \longrightarrow 12$**	9	−5
100	**$4 \longrightarrow 10$**	2	−8	91.82	$12 \longrightarrow 8$	−5	−8	83.07	$11 \longrightarrow 2$	−8	−17
100	**$4 \longrightarrow 14$**	8	−6	91.68	$3 \longrightarrow 14$	1	−12	82.68	$12 \longrightarrow 2$	−10	−2
100	**$5 \longrightarrow 9$**	6	−14	91.56	$1 \longrightarrow 12$	−23	−7	82.56	$3 \longrightarrow 11$	8	−20
100	$5 \longrightarrow 11$	9	−9	**91.34**	**$7 \longrightarrow 10$**	−5	−2	82.29	$13 \longrightarrow 1$	−10	−10
100	**$6 \longrightarrow 9$**	5	−10	91.02	$13 \longrightarrow 5$	10	−16	81.73	$6 \longrightarrow 12$	8	−9
100	**$7 \longrightarrow 12$**	−7	−7	90.59	$2 \longrightarrow 10$	−10	−8	81.10	$13 \longrightarrow 2$	−10	−20
100	$8 \longrightarrow 12$	−2	−10	**90.51**	**$10 \longrightarrow 4$**	6	−10	79.80	$6 \longrightarrow 10$	−2	−7
100	**$9 \longrightarrow 1$**	10	−16	**90.26**	**$12 \longrightarrow 4$**	2	−3	**79.67**	**$14 \longrightarrow 4$**	−1	−13
100	**$9 \longrightarrow 3$**	10	−6	90.01	$11 \longrightarrow 8$	−9	−19	79.13	$9 \longrightarrow 8$	−8	−4
100	**$9 \longrightarrow 5$**	9	−8	89.53	$12 \longrightarrow 6$	−1	−7	**77.06**	**$13 \longrightarrow 7$**	6	−12
100	**$9 \longrightarrow 6$**	2	−7	**89.44**	**$4 \longrightarrow 11$**	−1	−13	77.02	$12 \longrightarrow 1$	−7	−4
100	**$11 \longrightarrow 4$**	1	−11	89.03	$5 \longrightarrow 14$	−9	−3	76.62	$14 \longrightarrow 3$	−5	−10
100	$12 \longrightarrow 5$	6	−12	88.89	$8 \longrightarrow 14$	9	−11	**76.57**	**$7 \longrightarrow 9$**	−5	−2
100	**$12 \longrightarrow 7$**	9	−5	88.55	$8 \longrightarrow 13$	1	−8	75.78	$10 \longrightarrow 1$	−9	−17
100	**$13 \longrightarrow 4$**	7	−4	88.45	$6 \longrightarrow 14$	−6	−4	75.34	$10 \longrightarrow 2$	−4	−6
100	$13 \longrightarrow 6$	10	−11	88.39	$6 \longrightarrow 13$	−7	−2	74.71	$1 \longrightarrow 11$	−5	−17
100	**$14 \longrightarrow 7$**	−8	−9	87.92	$3 \longrightarrow 13$	0	−18	73.18	$2 \longrightarrow 14$	2	−8
99.43	**$4 \longrightarrow 9$**	3	−11	**87.89**	**$7 \longrightarrow 14$**	4	−2	72.72	$11 \longrightarrow 5$	−8	−11
99.39	**$11 \longrightarrow 6$**	2	−6	87.76	$11 \longrightarrow 3$	9	−5	72.71	$1 \longrightarrow 13$	−7	−7
99.33	**$6 \longrightarrow 11$**	4	−7	86.89	$10 \longrightarrow 3$	10	−20	**72.46**	**$14 \longrightarrow 6$**	−10	−20
97.80	**$9 \longrightarrow 7$**	10	−7	86.73	$13 \longrightarrow 3$	−5	−3	72.01	$1 \longrightarrow 14$	0	−9
95.84	$5 \longrightarrow 13$	10	−2	86.49	$2 \longrightarrow 11$	10	−11	69.76	$11 \longrightarrow 1$	−2	−6
95.58	$8 \longrightarrow 10$	6	−3	86.10	$5 \longrightarrow 12$	−2	−20	69.41	$1 \longrightarrow 10$	2	−10
95.30	$8 \longrightarrow 11$	5	−13	85.77	$5 \longrightarrow 10$	6	−6	**66.96**	**$10 \longrightarrow 7$**	−8	−7
94.51	**$8 \longrightarrow 9$**	−9	−9	**85.57**	**$3 \longrightarrow 9$**	7	−13	**62.50**	**$9 \longrightarrow 4$**	−6	−12
94.30	$12 \longrightarrow 3$	9	−7	85.54	$3 \longrightarrow 10$	−3	−20	52.64	$14 \longrightarrow 8$	−4	−5
93.42	**$4 \longrightarrow 13$**	9	−20	84.85	$10 \longrightarrow 5$	1	−6	**42.80**	**$9 \longrightarrow 2$**	−12	−20
93.28	$3 \longrightarrow 12$	10	−11	84.53	$2 \longrightarrow 12$	−10	−8	41.11	$10 \longrightarrow 6$	−8	−17
92.89	**$2 \longrightarrow 9$**	−8	−10	84.24	$2 \longrightarrow 13$	−1	−14	**24.96**	**$11 \longrightarrow 7$**	−5	−11
92.87	$13 \longrightarrow 8$	−1	−9	**84.21**	**$7 \longrightarrow 13$**	5	−6	16.54	$14 \longrightarrow 5$	−10	−13
92.54	$14 \longrightarrow 1$	2	−5	83.63	$14 \longrightarrow 2$	1	−12	2.72	$10 \longrightarrow 8$	−7	−11

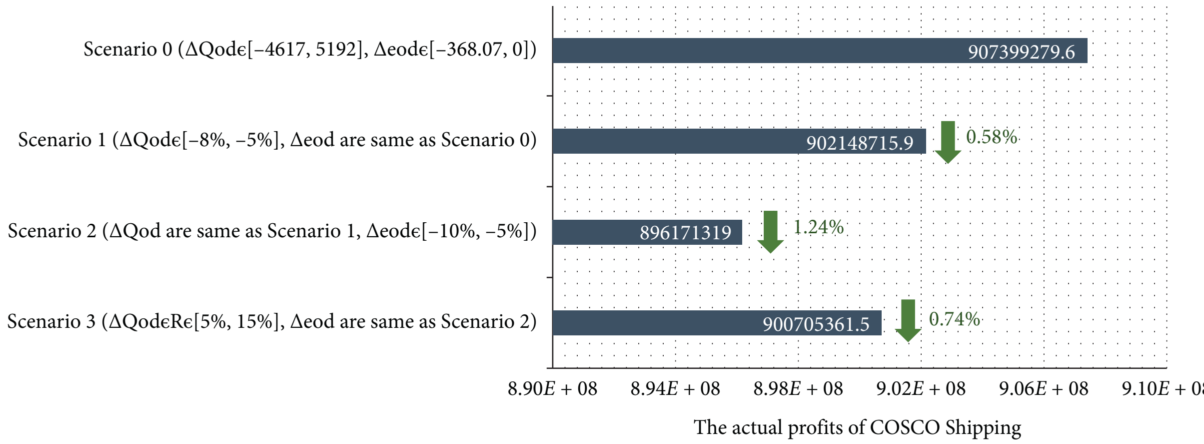


Figure 7: The actual profits of COSCO Shipping in Scenarios 1–3.

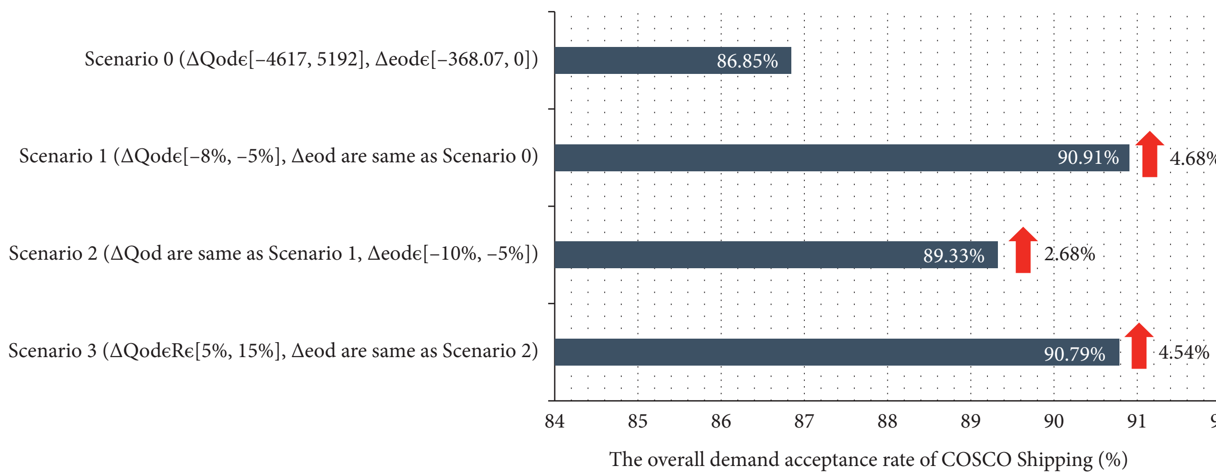


Figure 8: The overall demand acceptance rate of COSCO Shipping in Scenarios 1–3.

configuration is found, the problems of selecting the demands and switching the paths are solved for this configuration by the GA-based algorithm, and the optimal flows and paths are found, for that network configuration. By this algorithm, a set of candidate solutions (populations) is retained in each iteration (a.k.a. generation or trial), and the best populations are identified based on the principle of "survival of the fittest" through genetic operations as selection, crossover, and mutation, forming a new generation of candidate solutions. This process is repeated until reaching the maximum number of iterations Gmax. Featured by the introduction of an efficient solution representation, the proposed GA-based algorithm is described in Figure 2, and the specific steps are detailed in the following analysis.

Step 1. Coding: the solution representation directly bears on the GA performance. Considering the features of decision variables with the inclusion of two terms: "path-based flow," the solution is subjected to natural number encoding. Here, each solution is divided into two terms. The first term refers to the possible cargo flow on the path $s^1_{o\,d}$ and $s^2_{o\,d}$ between an O-D port pair. The second term refers to the transshipment port t where the secondary path $s^2_{o\,d}$ can be integrated into the primary path $s^1_{o\,d}$. Figure 3 illustrates a typical solution to the LSN design problem in the NO phase. The transshipment port t belongs to the nodes except for the nonduplicated ports and the origin and destination ports on the path $s^1_{o\,d}$ and $s^2_{o\,d}$, that is, the same nodes between the path $s^1_{o\,d}$ and $s^2_{o\,d}$ other than the port o and d.

Step 2. Fitness function: each solution satisfying the constraints is deemed as a chromosome. This paper attempts to minimize the difference between the operation costs and the temporal revenues. Here, the fitness function is set up based on the reciprocal of the objective function in equation (19). The fitness values are ranked in ascending order to find the maximum value.

Step 3. Selection: before crossover, two parent chromosomes are selected based on fitness. Then, a roulette selection procedure is adopted for our solution framework. First, calculate the fitness f_c of each chromosome c by the fitness function. Second, calculate the selection probability

Table 4: The results of demand acceptance rate of COSCO Shipping in Scenario 3.

$o \longrightarrow d$	G^3 (%)	$o \longrightarrow d$	G^3 (%)	$o \longrightarrow d$	G^3 (%)	$o \longrightarrow d$	G^3 (%)
1 ⟶ 9	**100**	**5 ⟶ 9**	**100**	**9 ⟶ 1**	**99.82**	12 ⟶ 1	100
1 ⟶ 10	100	5 ⟶ 10	100	**9 ⟶ 2**	**95.34**	12 ⟶ 2	94.59
1 ⟶ 11	88.36	5 ⟶ 11	97.36	**9 ⟶ 3**	**93.99**	12 ⟶ 3	75.22
1 ⟶ 12	58.72	5 ⟶ 12	85.31	**9 ⟶ 4**	**97.66**	12 ⟶ 4	96.80
1 ⟶ 13	94.67	5 ⟶ 13	85.95	**9 ⟶ 5**	**98.62**	12 ⟶ 5	100
1 ⟶ 14	92.95	5 ⟶ 14	98.90	**9 ⟶ 6**	**80.98**	**12 ⟶ 6**	**97.61**
2 ⟶ 9	**92.66**	**6 ⟶ 9**	**84.01**	**9 ⟶ 7**	**95.76**	12 ⟶ 7	85.42
2 ⟶ 10	91.20	**6 ⟶ 10**	**99.02**	**9 ⟶ 8**	**100**	12 ⟶ 8	34.14
2 ⟶ 11	100	**6 ⟶ 11**	**99.73**	10 ⟶ 1	93.78	13 ⟶ 1	98.42
2 ⟶ 12	98.72	**6 ⟶ 12**	**83.19**	10 ⟶ 2	100	13 ⟶ 2	80.48
2 ⟶ 13	66.33	**6 ⟶ 13**	**76.49**	10 ⟶ 3	98.11	13 ⟶ 3	96.02
2 ⟶ 14	95.04	**6 ⟶ 14**	**94.64**	10 ⟶ 4	88.41	13 ⟶ 4	93.05
3 ⟶ 9	**87.81**	**7 ⟶ 9**	**92.29**	10 ⟶ 5	96.29	13 ⟶ 5	72.51
3 ⟶ 10	87.15	7 ⟶ 10	98.01	**10 ⟶ 6**	**93.85**	**13 ⟶ 6**	**98.27**
3 ⟶ 11	95.77	7 ⟶ 11	97.02	10 ⟶ 7	79.55	13 ⟶ 7	34.47
3 ⟶ 12	96.02	7 ⟶ 12	82.89	10 ⟶ 8	83.06	13 ⟶ 8	96.46
3 ⟶ 13	90.79	7 ⟶ 13	87.13	11 ⟶ 1	87.90	14 ⟶ 1	76.08
3 ⟶ 14	95.95	7 ⟶ 14	88.28	11 ⟶ 2	41.85	14 ⟶ 2	39.21
4 ⟶ 9	**98.36**	**8 ⟶ 9**	**99.54**	11 ⟶ 3	86.12	14 ⟶ 3	91.62
4 ⟶ 10	84.56	8 ⟶ 10	82.82	11 ⟶ 4	61.80	14 ⟶ 4	84.47
4 ⟶ 11	100	8 ⟶ 11	95.76	11 ⟶ 5	84.72	14 ⟶ 5	93.58
4 ⟶ 12	98.95	8 ⟶ 12	100	**11 ⟶ 6**	**91.51**	**14 ⟶ 6**	**100**
4 ⟶ 13	91.74	8 ⟶ 13	96.66	11 ⟶ 7	91.30	14 ⟶ 7	82.76
4 ⟶ 14	100	8 ⟶ 14	86.66	11 ⟶ 8	79.34	14 ⟶ 8	66.21

$P_r^c = f_c / \sum_c f_c$ Prc for each chromosome. Third, calculate the cumulative probability $q_c = \sum_{i=1}^{c} P_r^c$, where $c = 1, 2, \ldots,$ pop_size and pop_size is the population size. Fourth, generate a random number r. Finally, if $r \leq q_1$, then select the first chromosome; otherwise, select the i-th chromosome such that $q_{i-1} < r \leq q_i$.

Step 4. Crossover: a single point crossover operator is used. In each crossover, we randomly select a cut-point in the chromosome and exchange the right parts of the two selected parent chromosomes to generate one or more children. The crossover probability is set as P_c, such that only P_c chromosomes undergo the crossover process. The crossover procedure is repeated until the number of child chromosomes reached pop_size.

Step 5. Mutation: through mutation, a new solution can be derived from an old solution. The mutation operator is employed in each generation of chromosomes at an equal probability (mutation rate) P_m. Specifically, the first term of the chromosome is flipped by the uniform mutation operator, and the second term alters one gene from its original value by the displacement mutation operator. An example of the crossover and mutation procedures is shown in Figure 4.

Step 6. Infeasible solution disposing: after crossover and mutation, if the solution to a chromosome is infeasible, the above steps are repeated from Step 2 until the terminal condition is satisfied. In the initial population, there might be some chromosomes that fail to obey one or more constraints. Obviously, the solutions naturally satisfy constraints (24)–(27) by the "path-based flow" coding. If a solution is found to be infeasible, it is necessary to verify it against constraints (20)–(23). If constraints (20)–(23) are not satisfied, the chromosome's fitness value should be lowered by the violation degree to the constraints.

6. Computational Experiment and Discussion

To assess the performance of the proposed algorithm on solving different test problems, the well-known standard dataset of the Persian Gulf trade lane that consists of 14 ports of COSCO Shipping in 2018 is used in the experiments. All data are generated from real information without distorting the original structure. The voyage distance ($d_{i_1 i_2}$) of any leg is measured by the BLM Shipping (see Figure 4).

(1) The THP $h \in H = \{4, 7\}$ and the EHP $r \in R = \{6, 9\}$ are all the considered hub ports along the Persian Gulf trade lane, according to the strategic agreement of COSCO Shipping.

(2) The voyage expense per containership of any leg is calculated as $c_{i_1 i_2} \in [16912.85,\ 2672083.84]$ (USD). Here, we adopt the containership named M7 with containership capacity $\pi = 10000$ (TEU). To calculate the voyage expense, we assume that the total fixed cost related to chartering and maintaining a vessel and providing salaries and insurances for seamen is 8000000 (USD/YEAR) [58]. The fuel cost is 167.454 (USD/NM) at the sailing speed of 22 (NM/HOUR) [66].

(3) The transit time of any leg $w_{i_1 i_2} \in [0.19, 21.29]$ (DAY) is obtained from the voyage distance ($d_{i_1 i_2}$) and the sailing speed of 22 (NM/HOUR) [66]. The fixed transit time for a voyage circle is set as $W \in [80, 180]$ (DAY).

(4) Considering that the government may control the freight capacity growth of maritime industry, we assume that the annual containership capacity that COSOCO Shipping can provide is limited at 1560000 (TEU/YEAR), according to the average containership capacity of COSCO Shipping in the past ten years. In other words, even if all the deployable containerships of COSCO Shipping are allocated to serve the investigated Persian Gulf trade lane with all the containerships full loaded for a whole year, the annual freight volume carried in the Persian Gulf trade lane cannot exceed 1560000 (TEU/YEAR). Therefore, in order to meet the annual capacity limit, the maximum containership capacity for a voyage circle is $\Omega = 1560000/(365/W)$ (TEU).

(5) The demand between each O-D port pair is Qod $\in$ [772, 79562] (TEU) and the freight rate of the corresponding demand is expected to be eod $\in$ [8.46, 1885.28] (USD/TEU).

(6) The loading/unloading expense at any port is set as ci $\in$ [1.21, 2.45] (USD/TEU).

(7) Within the designed transit time for a voyage circle $W = 91$ (DAY) in NO phase, the demand variation is ΔQod $\in$ [−4617, 5192] (TEU) and the freight rate variation is Δeod $\in$ [−368.07, 0] (USD/TEU) for each O-D port pair.

6.1. Comparison between LSNs in NA and NO Phases

6.1.1. The LSN in NA Phase. The results of models (I)~(II) are calculated by ILOG-CPLEX 12.5. Given the fixed limit of annual containership capacity controlled by the government, if the transit time of a voyage circle W is reduced, the service frequency of containership within a year will increase, and thus, the maximum containership capacity for a voyage circle Ω will fall, exerting a pressure on the shipping capacity for COSCO Shipping.

30 different $\{W, \Omega\}$ combinations are tested. The results are listed in Table 2. Here, for simplicity, the route design based on cooperation with THPs is called as G^1, while the route design based on cooperation with EHPs is called as G^2. Since the $\{W, \Omega\}$ combination changes in the same direction, the predicted profits of the LSN based on the THPs (G^1) increased with $\{W, \Omega\}$ and remained at 1851381648(USD) after $\{W = 155, \Omega = 662466\}$ reached the upper bound. By contrast, the predicted profits of G^1 minimized at 1817199741(USD) when the $\{W = 92, \Omega = 393205\}$ reached the lower bound. Any further drop of $\{W, \Omega\}$ made G^1 insolvable, i.e., no feasible solutions can be found. The same trend is observed in the LSN for the EHP (G^2). Moreover, the running time (Time) and deviation (Gap) of both models (I)~(II) are within the acceptable range.

To compare the maximum predicted profits in NA phase, the G^1 and G^2 results of COSCO Shipping are shown in Figure 5 when the combination is selected at $\{W = 155, \Omega = 662466\}$.

The total profit is fixed and predicted against the demands and freight rates between the origin and destination ports. Actually, the optimization of G^1 and G^2 is aimed at minimizing the installation cost. Through comparison, it is concluded as follows. First, in G^1, each containership calls twice at all the THPs. Similarly, containerships call twice at all the EHPs in G^2. By calling twice at hub ports, the voyage distance per leg can be shortened and save fuel cost. Second, contrary to the stereotype that calling at the THPs minimizes the installation cost, the total cost of G^1 is greater than that of G^2.

6.1.2. The LSN in NO Phase. After comparing the predicted profits, we took G^2 as the primary route, while G^1 as the secondary route. The LSN in the NO phase is called as G^3 for simplicity. The parameters for model solution are set as follows: the maximum number of iterations $G\max = 8000$, the population size pop_size = 100, the crossover probability $P_c = 0.90$, and the mutation probability $P_m = 0.01$. Then, the convergence of G^3 in different scenarios (see Figure 6) is run on Matlab R2013a on a Lenovo laptop with Intel® Core™ i5-6500 Processor (3.20 GHz; 8 GB RAM).

In the NO phase, the actual profit of COSCO Shipping is 907399279.57 (USD) when $\Delta Q_{od} \in [-4617, 5192]$ (TEU) and $\Delta e_{od} \in [-368.07, 0]$ (USD/TEU). Table 3 shows how COSCO Shipping adjusted G^3 based on the primary route and the secondary route. The overall demand acceptance rate is 86.85%, indicating that demand rejection is necessary when maximizing profits.

In addition to ΔQ_{od} and Δe_{od}, containership deployment and route design also influence the shipping capacity utilization rate of COSCO Shipping, making it difficult to observe how the shipping company selectively accepts the demand. Hence, the acceptance rates of the demand between different O-D pairs are contrasted in detail, revealing that the demand variation ΔQ_{od} has a decisive impact: the COSCO Shipping accepts more demand at higher ΔQ_{od}, while rejects more at lower ΔQ_{od}. Therefore, the demand variation has a greater impact than the freight rate change on the decision-making of demand acceptance. Furthermore, without considering the profitability of accepting the demand of certain O-D pairs, the high demand acceptance rate concentrated on the demand that must flow through the hub ports {4, 6, 7, 9}, as highlighted in bold format in Table 3. In addition, the primary and secondary routes, respectively, carried 67.5% and 32.5% of the total demand accepted by COSCO Shipping. The result proves that the primary paths are fundamental to the LSN optimization, while the secondary paths are a reasonable complement to the merged paths.

6.2. The LSN in NO Phase under Different Scenarios. The LSN in NO phase (G^3) in Section 6.1 (when $\Delta Q_{od} \in [-4617, 5192]$ (TEU) and $\Delta e_{od} \in [-368.07, 0]$ (USD/TEU)) is taken as Scenario 0. Three more scenarios are configured to further investigate the effect of ΔQ_{od} and Δe_{od} on G^3.

Scenario 1: all ΔQ_{od} are [5%, 8%] lower than those in Scenario 0; all Δe_{od} are the same as those in Scenario 0

Scenario 2: all ΔQ_{od} are the same as those in Scenario 1; all Δe_{od} are [5%, 8%] lower than those in Scenario 1

Scenario 3: all ΔQ_{od} are [5%, 15%] higher than those when the EHP $r \in R = \{6, 9\}$ are taken as the origin and destination ports; all Δe_{od} are the same as those in Scenario 2

Under Scenarios 1–3, the actual profits of COSCO Shipping are 902148715.92(USD), 896171319.02(USD), and 900705361.54(USD), respectively, down by 0.58%, 1.24%, and 0.74% from those in Scenario 0 (see Figure 7). In general, the decline in ΔQ_{od} and Δe_{od} only causes minor negative impacts on the actual profits. It is hard to say that the fluctuations of market indicators have few relationships with the actual profits of shipping companies. In fact, without the LSNs optimization measures such as demands rejection and flow integration, the negative impacts can be very significant. Therefore, it is safe to say that the negative impacts of ΔQ_{od} and Δe_{od} on the actual profits can be ameliorated by LSNs optimization measures. In other words, the decision-making process comprising NA phase and NO phase proposed in this paper can efficiently help the merged shipping companies reduce the negative impacts of depressed market.

Under Scenarios 1–3, the overall demand acceptance rates of COSCO Shipping are 90.91%, 89.33%, and 90.79%, respectively, up by 4.68%, 2.86%, and 4.54% from those in Scenario 0 (see Figure 8). By comparing the demand acceptance rate in Scenarios 0 and 1, one can find that the shipping company may accept more demand when the overall demand level decreases, which seems to be contradictive with the observation in Section 6.1. However, if we compare the demand acceptance rate in Scenarios 2 and 3, it can be revealed that the observation in Section 6.1 that shipping company accepts more demand at higher ΔQ_{od} and only holds when the overall freight rate level is low. Generally, in depressed market where both quantities and freight rates of demands are lower, the merged shipping company should reject more demand. Therefore, the demand rejection decisions should be adjusted according to both demands and freight rates. The shipping must focus on the survey of market indicators based on the historical data (as well as experts' knowledge of the market and management policies).

Finally, the results indicate that the shipping companies should attach more importance to EHPs when designing and optimizing the LSNs. On the one hand, EHPs are more likely to generate demand because they usually locate in rapidly developing economies. Scenario 3 assumes an increase of [5%, 15%] in the demands that take the EHPs as the origin and destination ports. The results show that the EHPs contributed to the 1.44% growth in demand, which leads to a 0.51% increase in the actual profits of shipping companies. On the other hand, shipping companies should increase the acceptance rate for the demands taking the EHPs as the origin and destination ports, as shown in Table 4.

7. Conclusion and Future Research

This paper aims to help COSCO Shipping address the LSN design problem with several hub ports to cooperate in regions along the Maritime Silk Road from the perspective of supply-side reform in China. For this purpose, we proposed two-phase optimization models for the LSN from strategic, tactical, and operational levels. Unlike traditional optimization approaches, our work divides the decision-making process into Network Assessment (NA) phase and Network Operation (NO) phase and considers external factors like market changes and hub port cooperation. In addition, our analyses highlighted two crucial operational measures: demand rejection and flow integration.

The optimization models for both phases are MILPs. The models in the NA phase are programmed in CPLEX, and those in the NO phase are solved by a GA-based algorithm. In light of the assessment of designing LSNs by cooperating with different types of hub ports based on predictions in the NA phase, a "path-based flow" model in the NO phase is specially developed and a set of easy-to-implement GA-based algorithm is designed to compute optimal solutions efficiently. Then, a computational experiment is performed on the Persian Gulf trade lane of COSCO Shipping. The experimental results prove the effectiveness of the GA and inspire the following countermeasures.

Firstly, when designing LSNs based on the cooperation with hub ports in the NA phase, the merged shipping company should increase the number of legs in the designed LSNs, e.g., calling twice at hub ports, in order to save the total installation cost. More importantly, the total installation cost could be further reduced by adjusting the selection of hub ports from THPs to EHPs. Secondly, the shipping company should reject more cargoes when the actual market is not satisfied, i.e., both quantities and freight rates of demands are lower. The scenario analyses show that the LSNs optimization measures including demands rejection and flow integration can efficiently help the shipping companies reduce the negative impacts of depressed market. Thirdly, the shipping company should increase the demand acceptance rate for the demands taking the hub ports, especially the EHPs as the origin and destination ports. In general, both the design and operation of LSNs should be flexibly adjusted according to demand prediction. If some ports are expected to generate greater demands than others, adjusting the hub of LSNs and accept more demand related to these EHPs could achieve better performance.

It must be noted that this study does not tackle all the decision-making problems at strategic, tactical, and operational levels of LSPs in NA and NO phases. To further optimize the LSNs, the future research will dig deep into the following issues: better prediction of future demand helps identify the emerging ports and optimize the LSNs; greater understanding of LSN structures, which consist of butterfly services, pendulum services, and even more complex services, helps explore more flexible and cost-efficient solutions; the operation adjustment after shipping company mergers or forming alliances deserves more attention.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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