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Research article

Liner alliance shipping network design model with shippers' choice inertia and empty container relocation

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Abstract: Liner companies have responded to escalating trade conflicts and the impact of the COVID-19 pandemic by forming alliances and implementing streamlined approaches to manage empty containers, which has strengthened the resilience of their supply chains. Meanwhile, shippers have grown more sensitive during these turbulent times. Motivated by the market situation, we investigate a liner alliance shipping network design problem considering the choice inertia of shippers and empty container relocation. To address this problem, we propose a bilevel programming model. The upper model aims to maximize the alliance's profit by optimizing the alliance's shipping network and fleet design scheme. The lower model focuses on optimizing the slot allocation scheme and the empty container relocation scheme. To ensure the sustainable operation of the alliance, we develop an inverse optimization model to allocate profits among alliance members. Furthermore, we design a differential evolution metaheuristic algorithm to solve the model. To validate the effectiveness of the proposed model and algorithm, numerical experiments are conducted using actual shipping data from the Asia-Western Europe shipping route. The results confirm the validity of the proposed model and algorithm, which can serve as a crucial decision-making reference for the daily operations of a liner shipping alliance.

Keywords: shipping network design; liner alliance; choice inertia; profit allocation; empty container relocation; inverse optimization; differential evolution (DE)

1. Introduction

Due to its cost advantages in transporting large-volume cargo over long distances, maritime transportation has become increasingly important in international trade with the advancement of economic globalization [1,2]. Currently, maritime transportation accounts for more than 80% of the world's trade volume [3]. Within the realm of maritime transportation, ocean container transportation has experienced remarkable growth since the advent of containers in the 1950s. Especially over the last three decades, container transportation has grown at a rate exceeding 8% annually, with over 5150 operational liners in 2017 [4]. In 2021, the volume of ocean transportation trade reached a staggering 11.08 billion tons, with ports worldwide handling over 800 million containers [5]. The existence of container transportation has facilitated the procurement of raw materials by the manufacturing industry from every corner of the world, enabling significant savings in manufacturing costs and a substantial improvement in productivity [6].

Liner companies, operating through their shipping networks, provide ocean container shipping services. To offer a consistent service, liner companies typically design and publish operational details regarding their shipping networks, including liner types, service frequencies, ports of call, calling sequences and freight rates, typically three to six months in advance [7]. Shippers can use this information to select the best liner company to transport their cargo. Consequently, the rationality and effectiveness of the shipping network have a direct impact on the profitability and future sustainability of liner companies, as well as the stability of supply chains and product prices [5]. It is, therefore, not surprising that creating a scientifically sound and efficient shipping network has become a focal point for the industry and academic community [8].

Motivated by the abovementioned background, we model a **C**ontainer **S**hipping **N**etwork **D**esign **P**roblem (CSNDP), filling a research gap in decision-making for CSNDP in light of changes in the global economic and trade environment. Aggressive outbreaks of COVID-19 have disrupted the scheduled operations of numerous enterprises [9] and have exerted mounting pressure on the shipping supply chain [10]. Over the past two years, the container transport market has experienced rare phenomena, such as shifts in demand structure, port construction, panic buying, truck driver shortages, and supply disruptions. Elmi et al. [11] reported a 4.1% decrease in international maritime volume in 2020, indicating the first decline since the 2008 financial crisis. Therefore, the establishment of a sustainable maritime supply chain has emerged as a novel research question in the post-COVID-19 epidemic era [12].

Currently, two factors require attention when liner companies design their shipping networks in the CSNDP. The first factor is the unstable demand in the shipping market, which presents challenges for liner companies to maintain continuous operation of shipping routes [13]. A notable example is the bankruptcy declaration of HANJIN, the sixth-largest liner company in the world, which occurred on August 31, 2016. To address demand fluctuations, liner companies should cooperate with each other to integrate liner resources and transportation demands, forming a liner alliance [14]. This form of cooperation not only assists in adapting to demand fluctuations but also enhances ship utilization, market share and economies of scale [15]. As of March 2020, the three major liner alliances (i.e., 2M Alliance, OCEAN Alliance and THE Alliance) accounted for nearly 80% of the total global market capacity [6]. In contrast to the decisions required when operating a liner company as an independent entity, the CSNDP within the context of a liner alliance necessitates designing a feasible network for each member of the alliance [16]. Meanwhile, the sharing of profits among members of the alliance must also be taken into account [17,18]. This means that apart from deciding on the shipping routes that each member of the alliance should manage, making efforts to allocate profits fairly among them is also essential. Therefore, we must rationally design a profit allocation mechanism to ensure the sustainable operation of the alliance in the CSNDP. These issues are certainly more complex than those addressed in the traditional CSNDP, which only focuses on individual liner companies [19,20].

Second, the uncertainty surrounding the supply capacity of transportation services has presented substantial challenges to shippers' daily operations in the post-COVID-19 epidemic era [21]. On the one hand, the stable supply of raw materials and the sale of finished products are highly dependent on transportation services, leading shippers to exhibit choice inertia when selecting a liner company. Choice inertia is often explained as a preference for maintaining stable and enduring relationships [22] and resistance to changing the current situation [23]. In ocean container shipping, choice inertia means that shippers tend to continue working with their existing shipping partners unless those liner companies fail to provide adequate transportation services [24]. Once a shipper has established a solid partnership and trusts a particular shipping company's services, they may continue choosing that company out of loyalty rather than easily shifting to other competitors. In psychological theory, the concept of choice inertia can be explained through several psychological principles, such as *cognitive ease* and *confirmation bias* [25]. Thus, it is common to observe liner companies experiencing losses during the off-season while still providing consistent transportation services. Influenced by this inertia, the alliance shipping network must be designed from a global perspective. This means that the alliance must be willing to endure a period of losses to ensure shipper loyalty to the alliance [26]. In this context, the shipping network design problem (SNDP) should involve multiple planning periods and ensure global rather than local optimization, which distinguishes it from the traditional network design problem that considers only a single planning period [27]. On the other hand, the relocation of empty containers presents significant challenges. Global trade activities often exhibit imbalances due to variations in comparative advantages among countries. This leads to surpluses of empty containers in certain ports, while others face shortages due to trade surpluses or deficits. Liner companies typically address these shortages by relocating empty containers from surplus ports. Inadequate management of empty container movements can have a substantial impact on freight rates and costs. A notable example is the COVID-19 outbreak in 2019, which affected numerous ports globally (e.g., the Port of Los Angeles in the United States). These ports experienced staff shortages and a significant decline in efficiency [28,29], resulting in poor empty container turnover and a sharp increase in container freight rates due to insufficient containers for cargo loading. However, during the off-season with reduced transportation demand, a surplus of empty containers emerges, compelling liner companies to store the excess [30]. Therefore, determining the storage and allocation of empty containers during alternating off-season and peak seasons also becomes a critical decision for liner companies.

These two factors have motivated us to conduct in-depth research on the CSNDP. In this paper, we refer to the CSNDP which considers both the liner alliance and the shippers' choice inertia factors as the **L**iner **A**lliance **S**hipping **N**etwork **D**esign problem considering the shipper's choice inertia (LASND). In the current complicated world environment, investigating LASND is helpful to establish a stable shipping system that maintains the stability of global supply chains while benefiting both liner companies and shippers. The research goal of this paper is to address LASND by replying to the following research questions.

1) How can the choice inertia of shippers be modeled?

2) How can LASND be modeled, considering the shipper's choice inertia and the relocation of

empty containers?

3) How can a model be developed to allocate profits among alliance members effectively and achieve sustainable operation of the alliance?

4) How can a suitable algorithm be designed to obtain an efficient solution for the proposed model?

Overall, this paper makes three contributions. First, a bilevel programming model is established to solve LASND. The upper-level model maximizes the net profit of the entire liner alliance by optimizing the shipping network design scheme (SNDS) and the fleet design scheme. The lower model optimizes the slot allocation scheme and the empty container relocation scheme. To the best of our knowledge, this is the first paper to simultaneously consider shippers' choice inertia, empty container relocation, and liner alliance factors in the modeling of LASND. In addition, the paper introduces the theory of choice preference into the alliance shipping network design problem.

Second, an inverse optimization model is developed to achieve profit allocation among the alliance members and ensure stable cooperation. The formation of the liner network is closely linked to the investment made by the members. Therefore, a reasonable profit allocation scheme must be devised to enable the alliance to maintain stable operations.

Third, we design a metaheuristic algorithm utilizing the differential evolution framework to efficiently solve the aforementioned model. Our algorithm incorporates CPLEX to solve the inverse optimization model during computation, aiming to maximize the profit of each liner company while achieving profit allocation among the members.

The remainder of this paper is organized as follows. Section 2 provides a brief review of the related literature. In Section 3, we introduce the basic concepts and assumptions underlying the LASND. Section 4 presents the establishment of a bilevel programming model to represent LASND. An efficient differential evolution algorithm designed to solve LASND is presented in Section 5. In Section 6, we conduct numerical experiments to evaluate the validity of the models and the algorithm. Finally, Section 7 summarizes the main findings of the paper, and potential research directions are discussed.

2. Literature review

Many scholars have researched the CSNDP and have produced a large number of studies since the 1990s. Table 1 briefly lists the research questions and solutions involved in the literature that we reviewed.

As the understanding of the problem deepens, scholars have further divided the CSNDP into three subproblems according to the different decision variables of the problem, namely, the fleet design and usage problem (FDUP), the shipping network design problem (SNDP) and the slot allocation problem (SAP). The FDUP contains a series of optimizations on the fleet design scheme, including the number, size and status of the liners (i.e., in service or in storage). The SNDP can be defined as follows: Given a set of ports, a set of O-D demands and a liner fleet, we construct a shipping network to maximize the profit of the fleet. SAP refers to a problem in which the liner company makes a cargo acceptance-rejection decision (i.e., decides how much cargo to load/unload at each port of call). Relevant research outcomes are reviewed here according to the development stage of the CSNDP. Systematic literature reviews can be found in Christiansen et al. [31], Wang and Meng [7] and Christiansen et al. [4]. Since LASND is a special CSNDP that considers the liner alliance factor, Section 2.1 provides an overview of the CSNDP, and Section 2.2 contains a review of the literature related to liner alliances.

Table 1. Conspectus of selected relevant literature.

Selected reference	Decision variable (s)			Additional constraint (s)				Solution method (s)	
	Fleet design and usage problem	Shipping network design problem	Slot allocation problem	Liner alliance	Shipper preference	Green shipping	Uncertainty	Heuristics	Exact solution method
Cho and Perakis [32]	√								√
Bendall and Stent [33]	√								√
Imai et al. [34]	√	√							√
Ronen [35]	√	√							√
Wang and Meng [36]		√						√	
Lu et al. [37]	√		√				√	√	
Wang and Meng [38]		√	√				√	√	
Brouer et al. [39]		√	√				√	√	
Karsten et al. [40]		√	√				√	√	
Pasha et al. [41]	√	√				√		√	
Duan et al. [42]	√	√			√			√	
Cheng and Wang [43]	√	√			√		√	√	
Dulebenets [44]	√			√			√	√	
Liu et al. [6]		√	√	√		√		√	
Song et al. [45]		√		√			√		√
Cariou and Guillotreau [46]	√			√			√		√
This paper	√	√	√	√	√			√	

2.1. Research on container shipping network design

Early scholars focused on one subproblem of the CSNDP and proposed their own research directions. For example, Cho and Perakis [32] focused on an FDUP and established a linear programming model to optimize the fleet size in a single planning period, where transportation demand was assumed to be fixed. As research has evolved, academia has begun in recent years to study the SNDP compounded by two or three of the FDUP, SNDP and SAP. In the context of the 2008 global economic crisis, optimizing the shipping network and reducing operating costs became research hotspots. During this time period, Imai et al. [34] investigated a compound problem of the FDUP and the SNDP considering the size of ships and container management. The problem was divided into two processes to find a solution: the shipping network design process and the container allocation process. Ronen [35] incorporated sailing speed factors into the model and jointly optimized the sailing speed of each voyage and the fleet size to reduce transportation costs. Furthermore, to obtain the optimal speed of the container ships on each waterway link, Wang and Meng [36] developed a nonlinear mixed integer programming model. An efficient outer-approximation method was proposed to solve the model.

In recent years, scholars have begun to shift from studying certain factors to studying uncertain factors (e.g., uncertain transportation demand and uncertain transportation time). Transportation demand has significant seasonal fluctuation characteristics and is also easily affected by economic oscillations. Moreover, changes in transportation demand directly affect the liner company's slot allocation scheme. To simulate the constraints on transportation time in the actual shipping service process, Wang and Meng [38] studied a compound problem of the SNDP and the SAP. They introduced delivery deadlines for each transportation demand and established a nonlinear and nonconvex mixed integer programming model. A heuristic algorithm based on column generation was presented to obtain a shipping network that meets the delivery deadline requirements. The seasonal fluctuation of shipping demand and freight rates affect the calling sequence of liners in a shipping route. To cope with this situation, Wang et al. [47] proposed an optimal calling port adjustment strategy. In the context of uncertain freight demand, Wang and Meng [48] studied the optimal pricing strategy of the liner company for each origin and destination pair under the limitation of uncertain spot capacity. The problem was formulated as a two-stage stochastic nonlinear and nonconvex programming model and solved by a tailored branch-and-bound-and-Benders algorithm. Recently, the proposal for carbon peak and carbon neutral goals has had a considerable impact on the transportation industry [49]. Motivated by this background, Pasha et al. [41] integrated the SNDP and the FDUP and produced an optimization model. Their model maximizes the total turnover profit considering carbon emissions and ship size optimization factors.

2.2. Research on shipper choice inertia

In the late 20th century, Jeuland [50] made significant contributions by introducing various formation mechanisms of choice inertia, which laid the foundation for a deeper understanding of choice behavior in the field of study. To date, extensive research on choice inertia has primarily concentrated on examining customer loyalty to brands (e.g., Zhao et al. [51]). In the field of transportation, investigations into this phenomenon date back to the early 20th century, with notable contributions from scholars such as Verplanken et al. [52] and Gärling and Axhausen [53]. In recent years, an increasing number of studies have begun to incorporate choice inertia into the model framework. The transportation field has witnessed an increased focus on incorporating travelers' inertia into traffic flow assignment models when studying transportation mode and route choices. For instance, Zhang and Yang [22] proposed a model to describe an inertial user equilibrium state, considering the diverse route choice inertia among travelers. Xie and Liu [54] approached a similar problem but integrated the randomness of traveler behavior into their model framework. More recently, Liu et al. [55] introduced the concept of traveler inertia into traffic forecasting.

Related research focusing specifically on choice inertia in the field of container transportation remains relatively scarce. In the maritime shipping field, shippers' time preference and reliability preference have been demonstrated to directly affect shippers' choice of transportation service providers [42]. Therefore, Cheng and Wang [43] considered the influence of shippers' time preference, cost preference and choice inertia on a shipping network design problem combination of the FDUP and SNDP. The authors assumed that shippers select the transportation service supplier through the discrete choice model based on their value judgments of the time and the cost. A heuristic genetic algorithm (GA) was designed to obtain high-performance solutions. Having been affected by COVID-19, freight rates have risen significantly [56,57], and transportation demand and transportation supply both show uncertainty [58]. Therefore, it is necessary to take shippers' choice inertia into consideration when designing the shipping network to reduce operating costs and to increase the utilization of transportation capacity.

2.3. Research on liner alliances

In the past decade, liner companies have formed alliances to boost ship utilization rates, to obtain a larger market share and to better deal with various risks [59]. In an early study, Agarwal and Ergun [15] first modeled a liner alliance SNDP and proposed a profit allocation mechanism to realize the stable operation of the alliance. Years later, Dulebenets [44] considered an alliance ship scheduling problem with time windows. The author established a mixed integer nonlinear model that minimizes the total shipping service cost, using CPLEX to solve the model after transforming the model into a linear programming problem through linearization techniques. Very recently, the government has further strengthened the control of carbon emissions for the protection of the environment. Therefore, the cost of carbon emissions cannot be neglected when designing an alliance shipping network. Liu et al. [6] took the carbon tax factor into consideration in alliance shipping network design and established a bi-objective green shipping network design model. The first objective is to maximize the benefits of the alliance, while the second objective is to balance the profit earned by alliance members.

In addition to quantitatively optimizing shipping services under the alliance state, more scholars have been committed to using theory to prove the effectiveness of an alliance or to discuss competition between alliances. For example, Zhang et al. [60] demonstrated that it is cheaper to establish an alliance during the repositioning process of empty containers than not to establish an alliance; this demonstration was accomplished by comparing the costs and benefits of the two models with an alliance and with nonalignment. Song et al. [45] theoretically proved that the liner alliance enables each member to benefit, which also directly explains the prosperity of the liner alliance. The authors discussed the conditions for liner companies with various price levels to form alliances on main shipping routes. A Nash equilibrium model was established and demonstrated that the liner alliance with low price levels was a win–win decision. High-priced liner companies are more willing to establish alliances with low-priced liner companies on the low-priced liner companies' main routes. The authors also showed that such cooperation would also benefit shippers. Due to overcapacity, liner alliances are able to deploy fleets more freely in the off-season for ocean shipping. Therefore, to obtain the most benefit from competition, Cariou and Guillotreau [46] applied monopoly theory to construct a game model among alliances. Their game model deploys fleets by predicting the decisions of competitors. However, various human-related factors (e.g., shippers' choice inertia) were not taken into consideration in their research.

2.4. Research gaps

Thus far, research on both shippers' choice inertia and liner alliances is rare, which is unfortunate in the current context. On the one hand, ignoring the shippers' choice inertia means that the alliance ignores the influence of shippers' choice inertia on future transportation demand. Especially in the context of the COVID-19 pandemic, shippers are extremely sensitive to the stability of the transportation service supply. Liner alliances can hardly make enough profits if they ignore the choice inertia of shippers. On the other hand, the emergence of liner alliances makes us consider the cooperation between liner companies and design shipping networks from the perspective of alliances. To fill the abovementioned two research gaps, our paper focuses on an alliance shipping network design problem (i.e., LASND) and establishes a bilevel programming model to describe the abovementioned scenario. Meanwhile, we also design the corresponding solution algorithm to achieve effective solutions for our model.

3. Problem description

3.1. Description of LASND

LASND contains three key elements: liner companies, cargo and ports of call. As mentioned earlier, a liner company usually designs the calling frequency, the set of ports of call, the calling sequence, the liner type and the freight rates every 3 to 6 months to provide relatively stable transportation services and to obtain stable transportation demand [61]. Therefore, the liner company needs to make a decision in LASND involving the optimization of elements related to the FDUP (i.e., liner number), the SDNP (i.e., set of ports of call, calling sequence) and the SAP (i.e., slot allocation scheme).

However, the decision-making process is different from the traditional SNDP once the alliance elements and shippers' choice inertia are introduced into the model. To maintain the stability of the supply chain in an uncertain global economic and trade environment, we assume here that shippers have choice inertia [24]. When the liner alliance meets the transportation demands of a shipper in the current time period, the shipper continues to cooperate with the liner alliance in the next time period, even if there is a more economical option. In contrast, once the shipper's transportation demand is not fully satisfied, the shipper never chooses the transportation service of the liner alliance in the foreseeable periods (usually 3 to 6 months). This makes it necessary in the context of LASND for liner alliances to adjust operational decisions in multiple time periods based on market conditions.

In addition, LASND is a problem involving multiple liner companies. The liner alliance is composed of several liner companies. The subnetworks of various liner companies are integrated to form the shipping network of the entire liner alliance. To avoid invalid internal competition, a waterway link can be operated by only one alliance member at a time. When the shipping network is determined, the alliance needs to develop a slot allocation scheme to maximize profit. In other words, each alliance member must make an acceptance-rejection decision for each transportation demand. After the transportation service is completed, the final problem that the alliance must address is the reasonable allocation of the alliance's profit among the members. The profit allocation mechanism is the key to the continuous operation of the alliance.

Based on the discussion above, LASND can be formulated as follows: The transportation demand for each time period is known. The liner alliance is constrained to maintain stable operation through the profit allocation mechanism. A model is constructed to realize the co-optimization of the FDUP, the SNDP and the SAP to maximize the sum of profits of the liner alliances for each time period. For convenience, the notation frequently used in this paper is listed in Table 2.

Table 2. The notations used in this paper.

Sets	
T	Set of all sub-planning periods, whose elements are denoted as t
G_k	Liner alliance SNDS *k*, which contains shipping network design schemes for each sub-planning period, i.e., $G_k := \{G_{k1}, G_{k2}, \cdots, G_{kN}\}$
G_{kt}	Liner alliance SNDS for sub-planning period *t* in network design scheme G_k
Ξ	Set of all feasible alliance SNDS, whose elements are denoted as G_k
V_{kt}	Set of port of call in scheme G_{kt}
E_{kt}	Set of links in scheme G_{kt}
M_{kt}	Set of virtual waterway links in scheme G_{kt}
W_{kt}	Set of O-D pairs in scheme G_{kt}, whose elements are (o,d)
C	Set of all alliance members, in which elements are denoted as $\tilde{i}$
$V_{k\tilde{i}t}$	Set of all ports of call for member $\tilde{i}$ in scheme G_{kt}
$E_{k\tilde{i}t}$	Set of all waterway links for member $\tilde{i}$ in scheme G_{kt}
$M_{k\tilde{i}t}$	Set of all virtual links for member $\tilde{i}$ in scheme G_{kt}
$W_{k\tilde{i}t}$	Set of O-D pairs for member $\tilde{i}$ in scheme G_{kt}
Parameters	
$(o,d,\tilde{i})$	Service for (o,d) offered by member $\tilde{i}$, where $\Gamma_{\tilde{i}} := \{(o,d,\tilde{i})\}$
e or (i,j)	Waterway link (also called 'leg' or 'edge') $e := (i,j)$
B_{ship}	Capacity of each liner
$q_t^{(o,d,\tilde{i})}$	Transportation demands obtained by member $\tilde{i}$ between ports at sub-planning period t
$q_t^{(o,d)}$	Transportation demands of the liner alliance between ports at sub-planning period t
dis_e	Distance of waterway link e
η	Selling price of unit fossil fuel
Variables	
x_k	A binary variable. When the alliance selects design scheme G_{kt}, x_k is equal to 1; otherwise, it equals 0
f	Service frequency weekly
$f_{et}^{(o,d,\tilde{i})}$	Laden container volume for (o,d) on link e offered by alliance member $\tilde{i}$ in scheme G_{kt}
$g_{et}^{(o,d,\tilde{i})}$	Empty container volume for (o,d) on link e offered by alliance member $\tilde{i}$ in scheme G_{kt}
$f_{et}^{(o,d)}$	Laden container volume for (o,d) on link e in scheme G_{kt}
p_{et}	Slot rental price of link e for each laden container (TEU) at period t
p'_{et}	Slot rental price of link e for each empty container (TEU) at period t
$s_t^{(o,d,\tilde{i})}$	Satisfaction rate of transport service $(o,d,\tilde{i})$ at period t

Continued on next page

Variables	
$s_t^{(o,d)}$	Satisfaction rate of transportation demand for the alliance from Port o to Port d at period t
$\delta_{ke\tilde{i}t}$	When $E_{k\tilde{i}t}$ contains link e, $\delta_{ke\tilde{i}t}=1$; otherwise, it equals 0
$N_{k\tilde{i}t}^{\text{ship}}$	Number of liners invested by member $\tilde{i}$ in network design scheme G_{kt}
$T_{k\tilde{i}t}$	Time for a liner to sail a cycle on the route operated by member $\tilde{i}$ in network design scheme G_{kt}
$T_{kt}^{(o,d)}$	Actual time between ports in network design scheme G_{kt}
$C_{k\tilde{i}t}^{\text{p}}$	Port-related cost for member $\tilde{i}$ in network design scheme G_{kt}
$C_{k\tilde{i}t}^{\text{fuel}}$	Ship-related cost for member $\tilde{i}$ in network design scheme G_{kt}
$r_{kt}^{(o,d)}$	Actual income per TEU from Port o to Port d in scheme G_{kt}
I_{kt}	Income of the alliance in network design scheme G_{kt}
C_{kt}^{week}	Total cost of the alliance in network design scheme G_{kt}

3.2. Definition of choice inertia of shippers

In daily operation, a liner alliance often abandons part of the transportation demand to maximize its profit. However, due to shippers' choice inertia, abandoned transportation demand does not resume in subsequent periods. This makes the liner alliance determine its slot allocation scheme from the perspective of the entire planning period when addressing the LASND. To characterize the shippers' choice inertia, a variable is defined here called the *satisfaction rate* of demand. It is defined as the ratio of cargo transport volume to cargo volume of shipping demand. Let T denote the set containing N sub-planning periods and $t\in[1,N]$ represent a specific sub-planning period. $f_t^{(o,d)}$ and $q_t^{(o,d)}$ represent the actual freight volume and transportation demand of the liner alliance from port o to port d in sub-planning period t, respectively. Then, we use $s_t^{(o,d)}$ $\left(0\le s_t^{(o,d)}\le 1\right)$ to denote the *satisfaction rate* of the shipping demand of origin-destination pair (o,d) at period t and $s_0^{(o,d)}$ to represent the initial satisfaction rate. At this point, $s_t^{(o,d)}$ can be calculated by Eqs. (1) and (2).

$$s_t^{(o,d)}=\frac{f_t^{(o,d)}}{q_t^{(o,d)}} \qquad \forall t\in T \tag{1}$$

More specifically, the shippers' choice inertia is abstracted into two properties as follows.

Property 1. For each (o,d), satisfaction rate $s_t^{(o,d)}$ remains the same when the liner alliance satisfies all transportation demand from the origin port to the destination port for any sub-planning period t.

$$\text{If } f_t^{(o,d)}=s_t^{(o,d)}\times q_t^{(o,d)}\text{, then } s_{t+1}^{(o,d)}=s_t^{(o,d)} \qquad \forall t\in[1,N-1] \tag{2}$$

Property 2. If the liner alliance cannot provide enough capacity for (o,d) in a certain sub-planning period *t*, satisfaction rate $s_t^{(o,d)}$ declines and does not recover in the following sub-planning periods.

$$\text{If } f_t^{(o,d)}<s_t^{(o,d)}\times q_t^{(o,d)}\text{, then } s_{t+1}^{(o,d)}\le\frac{f_t^{(o,d)}}{q_t^{(o,d)}} \qquad \forall t\in[1,N-1] \tag{3}$$

Since the transportation demand of an alliance comes from different members, we let $\tilde{i}$ denote an alliance member and C denote the set of all members; $(o,d,\tilde{i})$ is the transportation service for (o,d) offered by member $\tilde{i}$. $q_t^{(o,d,\tilde{i})}$ and $s_t^{(o,d,\tilde{i})}$ denote the actual transportation volume and satisfaction rate for (o,d) offered by member $\tilde{i}$ at sub-planning period t, respectively. Then, the following relationship exists between the transportation demand and the satisfaction rate of the alliance and the shipping demand and the satisfaction rate of each member, as shown in Eqs. (4) and (5).

$$q_t^{(o,d)} = \sum_{\tilde{i}\in C} q_t^{(o,d,\tilde{i})} \qquad \forall t \in T \tag{4}$$

$$s_t^{(o,d)} = s_t^{(o,d,\tilde{i})} \qquad \forall t \in T, \tilde{i} \in C \tag{5}$$

3.3. Definition of the liner alliance shipping network

The shipping network of a liner alliance composed of three liner companies is shown in Figure 1(a). Each node represents a port, while each directed line represents a waterway link. There are three shipping routes distinguished by different colors, and the routes of all liner companies form the alliance's shipping network. A classic assumption is reiterated here that a waterway link is independently operated by one liner company to avoid ineffective internal competition [21]. Figure 1(b) shows a shipping route containing 8 ports. Liners depart from Port 1 and return to Port 1, where the calling ports are in a fixed sequence. For convenience, a complete shipping route can be divided into a forward sub-route and a backward sub-route according to the sailing direction. It is customary for Chinese liner companies to refer to sub-routes from China to foreign countries as forward sub-routes.

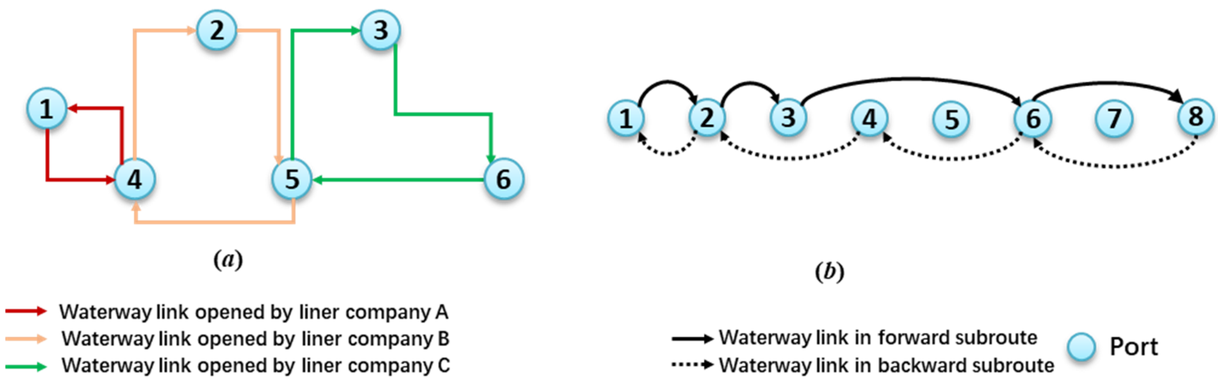

Figure 1. An alliance shipping network design scheme (SNDS) (a) and a shipping route (b).

For modeling convenience, we let $G_k := (G_{k1}, G_{k2}, \cdots G_{kN})$ represent the alliance SNDS k, the element G_{kt} denotes scheme k at sub-planning period t, and Ξ is a set containing all feasible shipping network design schemes. V_{kt} represents the set of ports of call, while E_{kt} denotes the set of links in network scheme G_{kt}. To facilitate the calculation of the cargo flow between two ports, several virtual links are introduced. For example, Figure 2 shows a shipping route (black arrows) and a virtual link (red arrows). The forward sub-route includes four waterway links (i.e., waterway links (1,2), (2,3), (3,6) and (6,8)). To calculate the actual shipping volume for the O-D pair $(1,8)$, a virtual waterway link (displayed in red) is created from Port 8 to Port 1. We let M_{kt} represent the set of virtual links in the network scheme G_{kt}, and we have $G_{kt} := (V_{kt}, E_{kt}, M_{kt})$. Moreover, to distinguish the operators of the various shipping routes, we set $G_{k\tilde{i}t} := (V_{k\tilde{i}t}, E_{k\tilde{i}t}, M_{k\tilde{i}t})$, and the subscript $\tilde{i}$ indicates that the corresponding set is related to alliance member $\tilde{i}$.

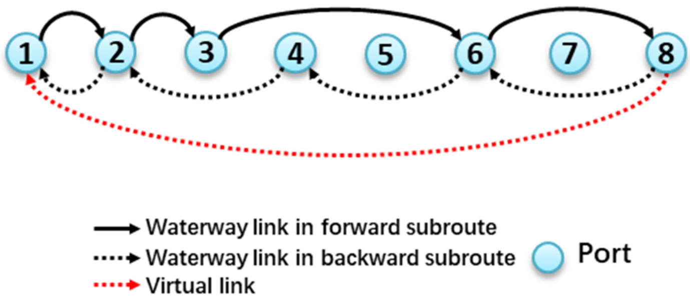

Figure 2. Virtual link (red dashed arrow) to describe the container flow from Port 8 to Port 1.

3.4. Profit allocation mechanism

It is impossible to form an alliance without a reasonable distribution of profits, which is the basis for the continued operation of the alliance. Since there is a division of labor among the alliance members, the services offered by one member may actually be provided by other members. In this case, the member providing the actual transportation service should transfer part of the profit to pay the member offering the service. Therefore, we define the profit allocation among alliance members as a paid rental activity of slots among the members. For example, if member A uses member B's liner to transport one TEU, it needs to pay member B a rental fee for one slot, which is referred to as the *transaction price*.

To ensure the fairness of profit distribution, we make the following assumptions on the conditions for stable operation of the liner alliance with reference to Agarwal and Ergun [15]: 1) Each alliance member sets a transaction price for each waterway link of the route it is responsible for operating according to the actual situation, and the price is applicable to all other members. 2) Based on the above price, the slot transaction made by each member to maximize their own interests is equivalent to the slot transaction that maximizes the alliance's profits. Let $e := (i, j)$ denote a waterway link (some may also refer to it as 'leg' or 'edge'); $r_t^{(o,d,\tilde{i})}$ indicates the revenue that member $\tilde{i}$ can obtain by undertaking the transportation service of one TEU for (o,d) in the planning period t; $r_t'^{(o,d,\tilde{i})}$ denotes the cost (e.g., handling cost, storage cost) that member $\tilde{i}$ can obtain by undertaking the transportation service of unit empty container (1 TEU) for (o,d) in the planning period t; $f_{(r,s)t}^{(o,d,\tilde{i})}$ or $f_{et}^{(o,d,\tilde{i})}$ indicates the laden container flow associated with $(o,d,\tilde{i})$ on link (r,s) (or e) in period t; $g_{(d,o)t}^{(o,d,\tilde{i})}$ or $g_{et}^{(o,d,\tilde{i})}$ denotes the empty container flow associated with $(o,d,\tilde{i})$ on link (r,s) (or e) in period t; p_{et} is the transaction price, which indicates the amount of money an alliance member should receive for providing transportation services on waterway link e for 1 TEU. $\delta_{ke\tilde{i}t}$ is an indicator variable that is equal to 1 when waterway link e is operated by alliance member

$\tilde{i}$ in shipping network design scheme G_{kt} and 0 otherwise.

$$I_{kt}=\sum_{\tilde{i}\in C}\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}},(d,o)\in M_{k\tilde{i}t}}\left[f_{(d,o)t}^{(o,d,\tilde{i})}r_t^{(o,d,\tilde{i})}-g_{(d,o)t}^{(o,d,\tilde{i})}r_t^{\prime(o,d,\tilde{i})}\right]\qquad\forall G_k\in\Xi,t\in T\qquad(6)$$

$$\begin{aligned}I_{k\tilde{i}t}=&\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}},(d,o)\in M_{k\tilde{i}t}}\left[f_{(d,o)t}^{(o,d,\tilde{i})}r_t^{(o,d,\tilde{i})}-g_{(d,o)t}^{(o,d,\tilde{i})}r_t^{\prime(o,d,\tilde{i})}\right]\\&+\sum_{t\in T}\sum_{e\in E_{kt}}p_{et}\left[\sum_{(o,d,\tilde{j})\in\Gamma\backslash\Gamma_{\tilde{i}}}f_{et}^{(o,d,\tilde{j})}\delta_{ke\tilde{i}t}-\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}}}f_{et}^{(o,d,\tilde{i})}\left(1-\delta_{ke\tilde{i}t}\right)\right]\qquad\forall G_k\in\Xi,t\in T\qquad(7)\\&+\sum_{t\in T}\sum_{e\in E_{kt}}p'_{et}\left[\sum_{(o,d,\tilde{j})\in\Gamma\backslash\Gamma_{\tilde{i}}}g_{et}^{(o,d,\tilde{j})}\delta_{ke\tilde{i}t}-\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}}}g_{et}^{(o,d,\tilde{i})}\left(1-\delta_{ke\tilde{i}t}\right)\right]\end{aligned}$$

Based on the above notations, the profit that the alliance and member $\tilde{i}$ can obtain under shipping network design scheme G_{kt} can be calculated by Constraints (6) and (7), respectively. Constraint (6) shows that the above profit allocation activities do not affect the profit of the alliance because each member sets a uniform transaction price for the other members. Constraint (7) shows that the total profit obtained by alliance member $\tilde{i}$ under network design scheme G_{kt} is equal to the profit obtained by providing transportation services plus (or minus) the profit obtained by providing services to other members (or the cost incurred due to other members of the alliance providing services on behalf of member $\tilde{i}$).

4. Model development

A model is developed for addressing LASND in this section. Except for the assumptions explained in the problem description section, we use the additional assumptions as follows.

1) In the liner alliance, each member invests in the same type of liner to form the shipping network [43].

2) Each waterway link can only be operated by one liner company [27]. This assumption can be relaxed by introducing more dimensions of decision variables.

3) The transportation demand of each member for each sub-planning period is known and is distributed equally to each week of the sub-planning period. The actual transportation needs that can be met change due to the inertia of the choice of the shipper. All transportation demands are converted into TEUs [62].

4) The initial satisfaction rate $s_0^{(o,d)}$ is set to 1.

5) The sailing speed of each liner is set to 18 kn.

6) The liner's calling time at each port is fixed at 18 hours [63].

4.1. Voyage time and cost calculation

In this section, we calculate the time and cost required for each voyage. We let v_e and dis_e denote the navigation speed on link e and the distance of e, respectively. $T_{k\tilde{i}te}$ denotes the sum of the sailing time of alliance member $\tilde{i}$ on waterway link e and the berthing time at the head node of link e in the network design scheme G_{kt}. $N_{k\tilde{i}t}^{\text{ship}}$ is the number of liners that should be invested in by alliance member $\tilde{i}$ under shipping network design scheme G_{kt}. The symbol $\lceil m \rceil$ denotes the minimum integer not less than the real number m. $T_{k\tilde{i}te}$ and $N_{k\tilde{i}t}^{\text{ship}}$ are calculated as shown in Constraints (8) and (9), respectively.

$$T_{k\tilde{i}te} = \frac{\text{dis}_e}{v_e} + 18 \qquad \forall \tilde{i} \in C, t \in T, G_k \in \Xi, e \in E_{k\tilde{i}t} \tag{8}$$

$$N_{k\tilde{i}t}^{\text{ship}} = \left\lceil \sum_{e \in E_{k\tilde{i}t}} \frac{T_{k\tilde{i}te}}{24 \times 7} f \right\rceil \qquad \forall \tilde{i} \in C, t \in T, G_k \in \Xi \tag{9}$$

The operating cost of member $\tilde{i}$ in scheme G_{kt} includes 3 parts: port-related cost, fuel cost and operating cost [27]. Let $|\bullet|$ denote the cardinality of a set; U indicates the capability of the liner; and α and β represent the fuel combustion efficiency and the price of fuel, respectively. $\gamma_1 \geq 0$ is the parameter related to the capital cost of the liner, and $\gamma_2 \in (0,1]$ is the parameter related to the economies of scale effect of the liner. Thus, $C_{k\tilde{i}t}^{\text{port}}$ is the port-related cost of member $\tilde{i}$ in scheme G_{kt}. It is closely associated with both the number of ports of call and the liner capacity. $C_{k\tilde{i}te}^{\text{fuel}}$ and $C_{k\tilde{i}te}^{\text{oper}}$ denote the sailing cost and ship-related cost for member $\tilde{i}$ on link a in scheme G_{kt}, respectively.

$$C_{k\tilde{i}t}^{\text{port}} = |V_{k\tilde{i}t}|(1.95U + 5200) \qquad \forall \tilde{i} \in C, t \in T, G_k \in \Xi \tag{10}$$

$$C_{k\tilde{i}te}^{\text{fuel}} = \alpha \beta f \sqrt{U} [v_e]^3 \qquad \forall \tilde{i} \in C, t \in T, G_k \in \Xi, e \in E_{k\tilde{i}t} \tag{11}$$

$$C_{k\tilde{i}te}^{\text{oper}} = \gamma_1 U^{\gamma_2} \qquad \forall \tilde{i} \in C, t \in T, G_k \in \Xi, e \in E_{k\tilde{i}t} \tag{12}$$

$$C_{kt}^{\text{week}} = \sum_{\tilde{i} \in C} \left[C_{k\tilde{i}t}^{\text{port}} + \sum_{e \in E_{k\tilde{i}t}} \frac{\left(C_{k\tilde{i}te}^{\text{oper}} + C_{k\tilde{i}te}^{\text{fuel}} N_{k\tilde{i}t}^{\text{ship}}\right) T_{k\tilde{i}te}}{24} \right] \qquad \forall G_k \in \Xi, t \in T \tag{13}$$

Based on the above notation, the three types of operations costs of alliance members can be calculated by Constraints (10)–(12). Finally, the weekly operating cost of the alliance under scheme G_{kt} can be written as Eq (13).

4.2. Model establishment

In this section, we construct the model for solving the LASND (LASNDM). To establish the model, we first introduce the following notation. The binary variable x_k is used to indicate whether to select scheme G_k. When liner alliances select shipping network design scheme G_k, variable $x_k = 1$. Otherwise, it equals 0. Note that the cardinality of set Ξ is extremely large, and it is impossible to directly use a commercial solver to solve the following model. Let T' represent the number of days included in each period, B_{ship} denote the capacity of the liner and $s_0^{(o,d)}$ be the initial satisfaction rate, which is determined based on the order fulfilment in the previous planning period. The mathematical expression of the LSANDM is shown below.

LASNDM:

$$\max_{(\mathbf{F},\mathbf{P})} z = \sum_{G_k \in \Xi} \left[\sum_{t \in T} \left(I_{kt} - \left\lceil \frac{T'}{7} \right\rceil \sum_{t \in T} C_{kt}^{\text{week}} \right) x_k \right] \tag{14}$$

s.t. Eqs (6)–(13),

$$x_k = \begin{cases} 1, & \text{If network design scheme } G_k \text{ is selected} \\ 0, & \text{Otherwise} \end{cases} \qquad \forall G_k \in \Xi \tag{15}$$

$$\sum_{G_k \in \Xi} x_k = 1 \tag{16}$$

$$\sum_{(r,s) \in E_{k\tilde{i}t} \cup M_{k\tilde{i}t}} f_{(r,s)t}^{(o,d,\tilde{i})} - \sum_{(s,r) \in E_{k\tilde{i}t} \cup M_{k\tilde{i}t}} f_{(s,r)t}^{(o,d,\tilde{i})} \le 0 \qquad \forall G_k \in \Xi,\ \tilde{i} \in C, t \in T, (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, s \in V_{kt} \tag{17}$$

$$\sum_{(r,s) \in E_{k\tilde{i}t} \cup M_{k\tilde{i}t}} g_{(r,s)t}^{(o,d,\tilde{i})} - \sum_{(s,r) \in E_{k\tilde{i}t} \cup M_{k\tilde{i}t}} g_{(s,r)t}^{(o,d,\tilde{i})} \le 0 \qquad \forall G_k \in \Xi,\ \tilde{i} \in C, t \in T, (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, s \in V_{kt} \tag{18}$$

$$\sum_{\tilde{i} \in C} \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}} f_{et}^{(o,d,\tilde{i})} + g_{et}^{(o,d,\tilde{i})} \le B_{\text{ship}} x_k \qquad \forall e \in E_{kt}, t \in T, G_k \in \Xi \tag{19}$$

$$\sum_{\tilde{i} \in C} \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}} \sum_{(r,s) \in E_{k\tilde{i}t}} \left(f_{(r,s)t}^{(o,d,\tilde{i})} + g_{(r,s)t}^{(o,d,\tilde{i})} \right) = \sum_{\tilde{i} \in C} \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}} \sum_{(s,r) \in E_{k\tilde{i}t}} \left(f_{(s,r)t}^{(o,d,\tilde{i})} + g_{(s,r)t}^{(o,d,\tilde{i})} \right) \quad \forall s \in V_{kt}, t \in T, G_k \in \Xi \tag{20}$$

$$f_{(d,o)t}^{(o,d,\tilde{i})} \le q_t^{(o,d,\tilde{i})} s_t^{(o,d)} \qquad \forall (d,o) \in M_{k\tilde{i}t}, (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, \tilde{i} \in C, t \in T, G_k \in \Xi \tag{21}$$

$$f_{(d,o)t}^{(o,d,\tilde{i})} - q_t^{(o,d,\tilde{i})} s_{t+1}^{(o,d)} = 0 \qquad \forall (d,o) \in M_{k\tilde{i}t}, (o,d,\tilde{i}) \in \Gamma_{\tilde{i}},\ \tilde{i} \in C, t \in [1, N-1], G_k \in \Xi \tag{22}$$

$$0 \le s_{t+1}^{(o,d)} \le s_t^{(o,d)} \le s_0^{(o,d)} \qquad \forall t \in [1, N-1], (d,o) \in M_{k\tilde{i}t}, \tilde{i} \in C, t \in T, G_k \in \Xi \tag{23}$$

$$f_{et}^{(o,d,\tilde{i})} = 0 \qquad \forall e \in M_{k\tilde{i}t} \setminus (d,o), t \in T, (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, \tilde{i} \in C, G_k \in \Xi \tag{24}$$

$$f_{et}^{(o,d,\tilde{i})}, g_{et}^{(o,d,\tilde{i})} \ge 0 \qquad \forall e \in E_{k\tilde{i}t} \cup M_{k\tilde{i}t}, t \in T, (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, \tilde{i} \in C, G_k \in \Xi \tag{25}$$

$$\mathbf{F} = \left(f_{et}^{(o,d,\tilde{i})} \right) = \arg\max_{\mathbf{Q}} \left\{ \sum_{G_k \in \Xi} x_k \left[\begin{array}{l} \sum_{t \in T} \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, (d,o) \in M_{k\tilde{i}t}} \tilde{f}_{(d,o)t}^{(o,d,\tilde{i})} r_t^{(o,d,\tilde{i})} \\ -\sum_{t \in T} \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, (d,o) \in M_{k\tilde{i}t}} \tilde{g}_{(d,o)t}^{(o,d,\tilde{i})} r_t'^{(o,d,\tilde{i})} \\ + \sum_{t \in T, e \in E_{kt}} p_{et} \left(\sum_{(o,d,\tilde{i}) \in \Gamma \setminus \Gamma_{\tilde{i}}} \tilde{f}_{et}^{(o,d,\tilde{i})} \delta_{ke\tilde{i}t} - \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}} \tilde{f}_{et}^{(o,d,\tilde{i})} \left(1 - \delta_{ke\tilde{i}t} \right) \right) \\ + \sum_{t \in T, e \in E_{kt}} p'_{et} \left(\sum_{(o,d,\tilde{i}) \in \Gamma \setminus \Gamma_{\tilde{i}}} \tilde{g}_{et}^{(o,d,\tilde{i})} \delta_{ke\tilde{i}t} - \sum_{(o,d,\tilde{i}) \in \Gamma_{\tilde{i}}} \tilde{g}_{et}^{(o,d,\tilde{i})} \left(1 - \delta_{ke\tilde{i}t} \right) \right) \end{array} \right], \forall \tilde{i} \in C \right\} \tag{26}$$

$$\mathbf{Q} = \left\{ \tilde{f}_{et}^{(o,d,\tilde{i})} \middle| s.t. \text{ Eqs } (17) - (25) \right\} \tag{27}$$

In the above, objective function (14) maximizes the liner alliance's total profit. Constraints (15) and (16) indicate that only one shipping network scheme is allowed to be selected. Constraints (17) and (18) ensure the balance of laden and empty container flows, respectively. Specifically, the inflow of containers in each port is equal to the outflow when virtual container flows are taken into consideration. Constraint (19) expresses capacity constraints; it requires that the container flow volume on each waterway link is not over the transport capacity that can be provided by the liner. Constraint (21) shows that the cargo flow volume cannot exceed the transportation demand. In other words, the freight volume on each link cannot surpass the transportation demand obtained by the entire alliance. Constraints (22) and (23) are equivalent to Constraints (2) and (3). Together, they describe the impact of shippers' choice inertia on transportation demand. Constraint (24) indicates that the container flow related to service $\left(o,d,\tilde{i}\right)$ is allocated only to virtual link $\left(d,o\right)$ for any virtual link $e\in M_{k\tilde{i}t}$. Constraint (25) guarantees the nonnegativity of any container flow.

In the model, vector $\mathbf{F}=\left(f_{et}^{\left(o,d,\tilde{i}\right)}\right)$ represents the optimal slot allocation scheme that maximizes the benefits of the liner alliance. However, the container accept-reject decisions of the members are still aimed at maximizing their own profits. Therefore, we further introduce Constraints (26) and (27) to design a reasonable mechanism. As mentioned earlier, the abovementioned mechanism aims to maximize the alliance's net profit while maximizing the members' interests. Constraint (26) requires that for each affiliate, the container acceptance-rejection decisions maximize the profits. The profit of each member is derived from the income from the provision of transportation services minus the expenses incurred by the profit allocation. Constraint (27) defines the feasible region for Constraint (26), which ensures that the profit allocation mechanism expressed by Constraint (26) does not violate the basic constraints of the network flow. In other words, $\tilde{f}_{(d,o)t}^{\left(o,d,\tilde{i}\right)}$ in constraint (27) is the cargo flow before the container transaction, and $f_{(d,o)t}^{\left(o,d,\tilde{i}\right)}$ in Constraints (17)–(25) is the cargo flow after the transaction is completed. Because they express different meanings, a wavy line is added above the decision variable $f_{(d,o)t}^{\left(o,d,\tilde{i}\right)}$ in Constraint (27).

5. Algorithm design

LASND has proven to be an NP-hard problem and cannot be solved exactly in a short time when the problem size is large [24,27,64]. Therefore, we first propose a model conversion method in Section 5.1. In Section 5.2, we discuss a metaheuristic (LASNDA) based on the converted model.

5.1. Procedure for model conversion

An analysis of the decision variables of the LASNDM reveals that the model is relatively easy to solve when vector $\left(\mathbf{X},\Delta\right)^{\mathrm{T}}$, where $\mathbf{X}=\left(x_k\right)$ and $\mathbf{\Delta}=\left(\delta_{ke\tilde{i}t}\right)$ are known. In other words, when a shipping network scheme is given, we can easily calculate the slot allocation scheme that maximizes the alliance's profit and allocate the profits among members accordingly. This makes it feasible to evaluate its performance for a given $\left(\mathbf{X},\Delta\right)^{\mathrm{T}}$. Taking advantage of this feature, the LSANDM can be divided into a two-stage model, say, [LASNDM-1] and [LASNDM-2]. Given a shipping network design scheme G_k, [LASNDM-1] is able to maximize the alliance's profit, while the decision variable is $\mathbf{F}$, where $\mathbf{F}=\left(f_{et}^{(o,d,\tilde{i})}\right)$. [LASNDM-2] is a linear programming, while the decision variable is $\mathbf{F}$.

LASNDM-1:

$$\max_{\mathbf{F}} z_1=\sum_{G_k\in\Xi}\left(I_k-C_k\right)x_k \tag{28}$$

$$s.t.\ \text{Eqs (6)–(13)},\ \mathbf{F}\in\mathbf{Q}' \tag{29}$$

$$\mathbf{Q}'=\left\{f_{et}^{(o,d,\tilde{i})}\,\middle|\,s.t.\ \text{Eqs (17)}-(25)\right\} \tag{30}$$

For any feasible solutions $(\mathbf{X},\Delta)^{\mathrm{T}}$, the optimization model solved by alliance members in the alliance can be established as [LASNDM-2].

LASNDM-2: For all $\tilde{i}\in C$,

$$\begin{aligned}\max_{\mathbf{F}} z_2=&\sum_{t\in T}\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}},(d,o)\in M_{k\tilde{i}t}}\left(f_{(d,o)t}^{(o,d,\tilde{i})}r_t^{(o,d,\tilde{i})}-g_{(d,o)t}^{(o,d,\tilde{i})}r_t'^{(o,d,\tilde{i})}\right)\\&+\sum_{t\in T}\sum_{e\in E_{kt}}p_{et}\left(\sum_{(o,d,\tilde{j})\in\Gamma\backslash\Gamma_{\tilde{i}}}f_{et}^{(o,d,\tilde{j})}\delta_{ke\tilde{i}t}-\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}}}f_{et}^{(o,d,\tilde{i})}\left(1-\delta_{ke\tilde{i}t}\right)\right)\\&+\sum_{t\in T}\sum_{e\in E_{kt}}p'_{et}\left(\sum_{(o,d,\tilde{j})\in\Gamma\backslash\Gamma_{\tilde{i}}}g_{et}^{(o,d,\tilde{j})}\delta_{ke\tilde{i}t}-\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}}}g_{et}^{(o,d,\tilde{i})}\left(1-\delta_{ke\tilde{i}t}\right)\right)\end{aligned} \tag{31}$$

$$s.t.\ \ \mathbf{F}\in\mathbf{Q}' \tag{32}$$

$$\mathbf{Q}'=\left\{f_{et}^{(o,d,\tilde{i})}\,\middle|\,s.t.\ \text{Eqs (17)}-(25)\right\} \tag{33}$$

According to the previous analysis, if $\mathbf{P}$ is reasonably determined, the profits of the liner alliance and the members reach the maximum at the same time. Therefore, if we substitute the optimal solution obtained from [LASNDM-1], say $\mathbf{F}^*$, into [LASNDM-2], [LASNDM-2] can determine the optimal transaction price, say $\mathbf{P}=\left(p_{et}\right)$. However, the abovementioned model with $\mathbf{P}$ as the parameter and $\mathbf{F}$ as the decision variable is exactly the opposite of our solution idea. This requires us to apply the inverse optimization approach proposed by Agarwal and Ergun [15] to transform [LANSDM-2] into its dual problem, say, [LASND-2T]. In this way, $\mathbf{P}$ becomes the decision variable of the new model and can be optimized. We denote $\boldsymbol{\gamma}=\left(\gamma_{rt}^{(o,d,\tilde{i})}\right)$, $\boldsymbol{\gamma}'=\left(\gamma_{rt}'^{(o,d,\tilde{i})}\right)$, $\boldsymbol{\xi}=\left(\xi_{et}\right)$, $\boldsymbol{\zeta}=\left(\zeta_{rt}\right)$ and $\boldsymbol{\omega}=\left(\omega_t^{(o,d,\tilde{i})}\right)$ as the multipliers associated with Constraints (17)–(21), respectively, and let $\bar{E}_{kt}:=\left\{e\in E_{kt}:\sum_{\tilde{i}\in C}\sum_{(o,d,\tilde{i})\in\Gamma_{\tilde{i}}}f_{et}^{*(o,d,\tilde{i})}+g_{et}^{*(o,d,\tilde{i})}<B_{\text{ship}}x_k\right\}$.

LASNDM-2T: For all member $\tilde{i}\in C$,

$$\gamma_{ot}^{(o,d,\tilde{i})}-\gamma_{dt}^{(o,d,\tilde{i})}+\omega_t^{(o,d,\tilde{i})}\geq r_t^{(o,d,\tilde{i})}\qquad \forall f_{(d,o)t}^{(o,d,\tilde{i})^*}\in R \tag{34}$$

$$\gamma_{ot}^{(o,d,\tilde{i})}-\gamma_{dt}^{(o,d,\tilde{i})}+\omega_t^{(o,d,\tilde{i})}=r_t^{(o,d,\tilde{i})}\qquad \forall f_{(d,o)t}^{(o,d,\tilde{i})^*}\in R_+ \tag{35}$$

$$\gamma_{ot}'^{(o,d,\tilde{i})} - \gamma_{dt}'^{(o,d,\tilde{i})} \geq r_t'^{(o,d,\tilde{i})} \qquad \forall g_{(d,o)t}^{(o,d,\tilde{i})^*} \in R' \tag{36}$$

$$\gamma_{ot}'^{(o,d,\tilde{i})} - \gamma_{dt}'^{(o,d,\tilde{i})} = r_t'^{(o,d,\tilde{i})} \qquad \forall g_{(d,o)t}^{(o,d,\tilde{i})^*} \in R_+' \tag{37}$$

$$\gamma_{ot}^{(o,d,\tilde{j})} - \gamma_{dt}^{(o,d,\tilde{j})} + \omega_t^{(o,d,\tilde{i})} \geq 0 \qquad \forall f_{(d,o)}^{(o,d,\tilde{j})^*} \in T \tag{38}$$

$$\gamma_{ot}^{(o,d,\tilde{j})} - \gamma_{dt}^{(o,d,\tilde{j})} + \omega_t^{(o,d,\tilde{i})} = 0 \qquad \forall f_{(d,o)}^{(o,d,\tilde{j})^*} \in T_+ \tag{39}$$

$$\gamma_{ot}'^{(o,d,\tilde{j})} - \gamma_{dt}'^{(o,d,\tilde{j})} \geq 0 \qquad \forall g_{(d,o)}^{(o,d,\tilde{j})^*} \in T' \tag{40}$$

$$\gamma_{ot}'^{(o,d,\tilde{j})} - \gamma_{dt}'^{(o,d,\tilde{j})} = 0 \qquad \forall g_{(d,o)}^{(o,d,\tilde{j})^*} \in T_+' \tag{41}$$

$$\gamma_{st}^{(o,d,\tilde{i})} - \gamma_{rt}^{(o,d,\tilde{i})} + \zeta_{st} - \zeta_{rt} + \xi_{et} - \delta_{keit} p_{et} \geq 0 \qquad \forall f_{(r,s)t}^{(o,d,\tilde{i})^*} \in U \tag{42}$$

$$\gamma_{st}^{(o,d,\tilde{i})} - \gamma_{rt}^{(o,d,\tilde{i})} + \zeta_{st} - \zeta_{rt} + \xi_{et} - \delta_{keit} p_{et} = 0 \qquad \forall f_{(r,s)t}^{(o,d,\tilde{i})^*} \in U_+ \tag{43}$$

$$\gamma_{st}'^{(o,d,\tilde{i})} - \gamma_{rt}'^{(o,d,\tilde{i})} + \zeta_{st} - \zeta_{rt} + \xi_{et} - \delta_{keit} p_{et}' \geq 0 \qquad \forall g_{(r,s)t}^{(o,d,\tilde{i})^*} \in U' \tag{44}$$

$$\gamma_{st}'^{(o,d,\tilde{i})} - \gamma_{rt}'^{(o,d,\tilde{i})} + \zeta_{st} - \zeta_{rt} + \xi_{et} - \delta_{keit} p_{et}' = 0 \qquad \forall g_{(r,s)t}^{(o,d,\tilde{i})^*} \in U_+' \tag{45}$$

$$\gamma_{st}^{(o,d,\tilde{j})} - \gamma_{rt}^{(o,d,\tilde{j})} + \zeta_{st} - \zeta_{rt} + \xi_{et} \geq -\left(1-\delta_{keit}\right) p_{et} \qquad \forall f_{(r,s)t}^{(o,d,\tilde{j})} \in Y \tag{46}$$

$$\gamma_{st}^{(o,d,\tilde{j})} - \gamma_{rt}^{(o,d,\tilde{j})} + \zeta_{st} - \zeta_{rt} + \xi_{et} = -\left(1-\delta_{keit}\right) p_{et} \qquad \forall f_{(r,s)t}^{(o,d,\tilde{j})} \in Y_+ \tag{47}$$

$$\gamma_{st}'^{(o,d,\tilde{i})} - \gamma_{rt}'^{(o,d,\tilde{i})} + \zeta_{st} - \zeta_{rt} + \xi_{et} \geq -\left(1-\delta_{keit}\right) p_{et}' \qquad \forall g_{(r,s)t}^{(o,d,\tilde{j})} \in Y' \tag{48}$$

$$\gamma_{st}'^{(o,d,\tilde{i})} - \gamma_{rt}'^{(o,d,\tilde{i})} + \zeta_{st} - \zeta_{rt} + \xi_{et} = -\left(1-\delta_{keit}\right) p_{et}' \qquad \forall g_{(r,s)t}^{(o,d,\tilde{j})} \in Y_+' \tag{49}$$

$$\gamma_{rt}^{(o,d,\tilde{i})} \geq 0 \qquad \forall r \in V_k, t \in T, \left(o,d,\tilde{i}\right) \in \Gamma_{\tilde{i}}, \tilde{i} \in C \tag{50}$$

$$\gamma_{rt}'^{(o,d,\tilde{i})} \geq 0 \qquad \forall r \in V_k, t \in T, \left(o,d,\tilde{i}\right) \in \Gamma_{\tilde{i}}, \tilde{i} \in C \tag{51}$$

$$\zeta_{rt} \geq 0 \qquad \forall r \in V_k, t \in T \tag{52}$$

$$\xi_{et} \geq 0 \qquad \forall e = \left(r,s\right) \in E_{kt}, t \in T \tag{53}$$

$$\xi_{et} = 0 \qquad \forall e = \left(r,s\right) \in \bar{E}_{kt}, t \in T \tag{54}$$

$$\omega_t^{(o,d,\tilde{i})} \geq 0 \qquad \forall e = \left(r,s\right) \in E_{kt}, t < N \tag{55}$$

$$\omega_t^{(o,d,\tilde{i})} = 0 \qquad \forall e = \left(r,s\right) \in E_{kt}, t = N \tag{56}$$

where

$$R := \left\{ f_{(d,o)t}^{(o,d,i)^*} \mid f_{(d,o)t}^{(o,d,i)^*} = 0, \forall \left(o,d,\tilde{i}\right) \in \Gamma_{\tilde{i}}, \left(d,o\right) \in M_{k\tilde{i}t}, t \in T \right\}$$

$$R_+ := \left\{ f_{(d,o)t}^{(o,d,i)^*} \mid f_{(d,o)t}^{(o,d,i)^*} > 0, \forall \left(o,d,\tilde{i}\right) \in \Gamma_{\tilde{i}}, \left(d,o\right) \in M_{k\tilde{i}t}, t \in T \right\}$$

$$R' := \left\{ g_{(d,o)t}^{(o,d,i)^*} \mid g_{(d,o)t}^{(o,d,i)^*} = 0, \forall \left(o,d,\tilde{i}\right) \in \Gamma_{\tilde{i}}, \left(d,o\right) \in M_{k\tilde{i}t}, t \in T \right\}$$

$$R_+' := \left\{ g_{(d,o)t}^{(o,d,i)^*} \mid g_{(d,o)t}^{(o,d,i)^*} > 0, \forall \left(o,d,\tilde{i}\right) \in \Gamma_{\tilde{i}}, \left(d,o\right) \in M_{k\tilde{i}t}, t \in T \right\}$$

$$T := \left\{ f_{(d,o)}^{(o,d,\tilde{j})^*} \mid f_{(d,o)}^{(o,d,\tilde{j})^*} = 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, (d,o) \in M_{kt} \setminus M_{k\tilde{i}t}, t \in T \right\}$$

$$T_+ := \left\{ f_{(d,o)}^{(o,d,\tilde{j})^*} \mid f_{(d,o)}^{(o,d,\tilde{j})^*} > 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, (d,o) \in M_{kt} \setminus M_{k\tilde{i}t}, t \in T \right\}$$

$$T' := \left\{ g_{(d,o)}^{(o,d,\tilde{j})^*} \mid g_{(d,o)}^{(o,d,\tilde{j})^*} = 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, (d,o) \in M_{kt} \setminus M_{k\tilde{i}t}, t \in T \right\}$$

$$T'_+ := \left\{ g_{(d,o)}^{(o,d,\tilde{j})^*} \mid g_{(d,o)}^{(o,d,\tilde{j})^*} > 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, (d,o) \in M_{kt} \setminus M_{k\tilde{i}t}, t \in T \right\}$$

$$U := \left\{ f_{et}^{(o,d,\tilde{i})^*} \mid f_{et}^{(o,d,\tilde{i})^*} = 0, \forall (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$U_+ := \left\{ f_{et}^{(o,d,\tilde{i})^*} \mid f_{et}^{(o,d,\tilde{i})^*} > 0, \forall (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$U' := \left\{ g_{et}^{(o,d,\tilde{i})^*} \mid g_{et}^{(o,d,\tilde{i})^*} = 0, \forall (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$U'_+ := \left\{ g_{et}^{(o,d,\tilde{i})^*} \mid g_{et}^{(o,d,\tilde{i})^*} > 0, \forall (o,d,\tilde{i}) \in \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$Y := \left\{ f_{et}^{(o,d,\tilde{j})^*} \mid f_{et}^{(o,d,\tilde{j})^*} = 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$Y_+ := \left\{ f_{et}^{(o,d,\tilde{j})^*} \mid f_{et}^{(o,d,\tilde{j})^*} > 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$Y' := \left\{ g_{et}^{(o,d,\tilde{j})^*} \mid g_{et}^{(o,d,\tilde{j})^*} = 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

$$Y'_+ := \left\{ g_{et}^{(o,d,\tilde{j})^*} \mid g_{et}^{(o,d,\tilde{j})^*} > 0, \forall (o,d,\tilde{j}) \in \Gamma \setminus \Gamma_{\tilde{i}}, e = (r,s) \in E_{kt}, t \in T \right\}$$

5.2. Framework for the designed algorithm

To solve this NP-hard problem, inspired by Agarwal and Ergun [15], a metaheuristic called LSANDA is designed in view of the GA framework. According to the above analysis, the model can be solved relatively simply once the vector $(\mathbf{X}, \Delta)^{\mathrm{T}}$ is determined. In other words, for any shipping network scheme, we can calculate and obtain the corresponding total profits of the alliance and the slot allocation scheme. Then, we can modify $(\mathbf{X}, \Delta)^{\mathrm{T}}$ according to the quality of the solution (i.e., the total profit of the alliance). The flow diagram of the proposed algorithm is presented in Figure 3. Specifically, we first randomly encode a feasible $(\mathbf{X}, \Delta)^{\mathrm{T}}$ as the individual and calculate the profit of the liner alliance as the fitness value. Then, we obtain $\mathbf{F}^*$ by solving [LASND-1]. Next, $\mathbf{F}^*$ is substituted into [LASNDM-2T] to obtain $\mathbf{P}^*$. The population continues to reproduce through selection, crossover and mutation operators. Finally, we obtain a satisfactory solution after repeated iterations. The algorithm stops iterating when a termination rule is triggered.

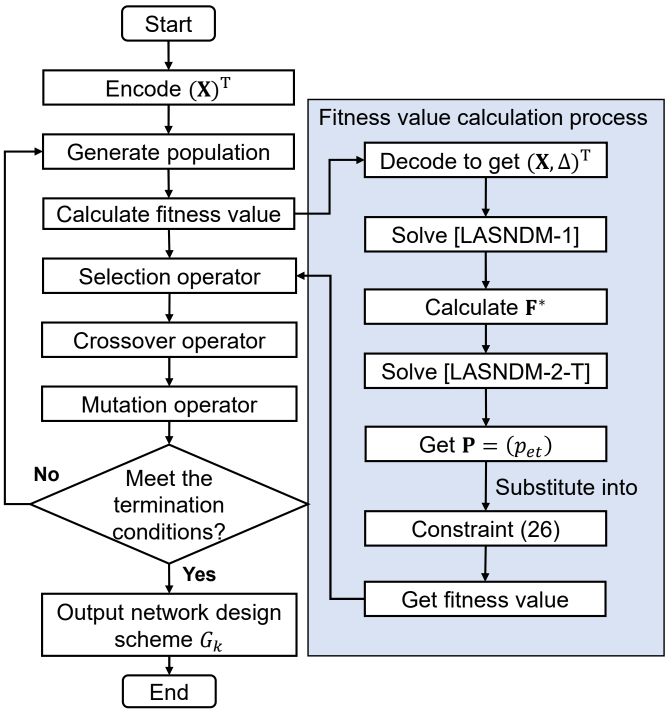

Figure 3. Flow chart of LSANDA.

5.3. Methods of encoding and decoding

The chromosome encoding method is shown in Figure 4 when the alliance is composed of only two members, namely, members $\tilde{i}$ and $\tilde{j}$. A chromosome represents a shipping network scheme operated by one alliance member and is divided into multiple sub-chromosomes according to different sub-planning periods. Let st_n denote the network design scheme at period $n \in T$. Each sub-chromosome contains five gene fragments, namely, sq_{n1} to sq_{n5}. sq_{n1} is a random permutation of integer numbers 1 to $\tilde{N}$, where $\tilde{N}$ is equal to the number of candidate ports. Gene fragments sq_{n2} to sq_{n5} are binary codes with the same length as sq_{n1}, which indicate whether the ports are berthed by liners. Specifically, sq_{n2} and sq_{n3} denote the forward and backward sub-routes of the shipping network operated by member $\tilde{i}$, respectively. Similarly, sq_{n4} and sq_{n5} represent the corresponding sub-routes operated by member $\tilde{j}$. The forward calling sequence is determined from left to right, while the calling sequence is the exact opposite for the backward sub-route. A value of 1 for the *i*th gene locus indicates that the *i*th port should be berthed. Otherwise, if the value of the *i*th gene locus equals 0, the liner does not berth at this port.

Figure 4 serves as an example here to clarify the decoding procedure. In the figure, there are 8 candidate ports shown in sq_{n1}. Reading the sq_{n2} reveals that the values of the 1st, 3rd and 5th gene loci are 1. Therefore, Ports 1, 3 and 5 are in the forward sub-route for member $\tilde{i}$ in the shipping network. According to the order of sq_{n1}, the forward sub-route is $\{(1,3),(3,5)\}$. Similarly, Ports 1, 2 and 5 are in the backward sub-route operated by member $\tilde{i}$. We reverse the sequence of sq_{n1} and obtain the calling sequence. The backward sub-route is $\{(5,2),(2,1)\}$. In this way, the shipping route for member $\tilde{i}$ is determined, i.e., $\{(1,3),(3,5),(5,2),(2,1)\}$. By using the same decoding method, we can obtain the route operated by member $\tilde{j}$ at period n as $\{(6,7),(7,8),(8,4),(4,3),(3,6)\}$.

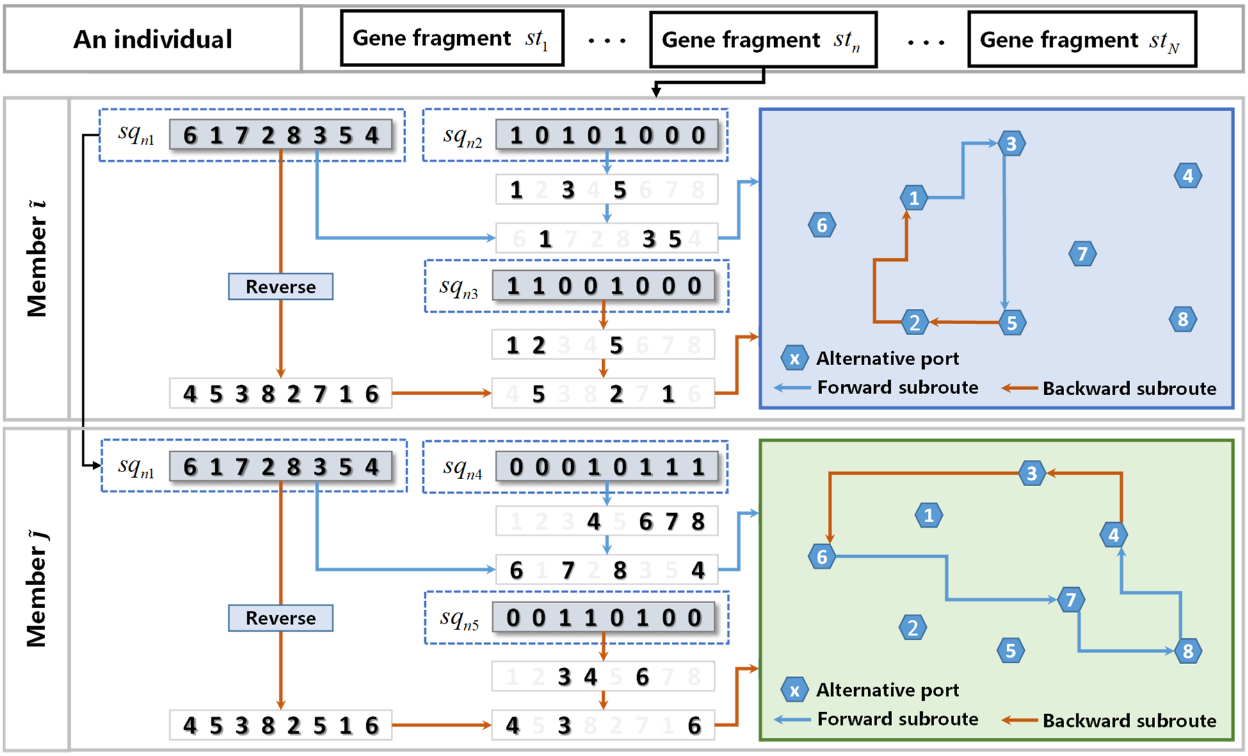

Figure 4. Methods of encoding and decoding.

5.4. Differential mutation, crossover and selection procedure

This section begins by introducing the differential mutation operator used in the differential evolution algorithm. The purpose of this operator is to generate a new individual by calculating the vector difference between two individuals sq_{ni}^{b} and sq_{ni}^{c} in the population and adding it to a third individual sq_{ni}^{a} $(i=1,\cdots,5)$. Let $PS \geq 3$ denote the population size. The differential mutation operator is executed k times, and the resulting sequence at period $n \in T$ is represented as vsq_n and can be expressed using Eq (57).

$$vsq_{ni} = sq_{ni}^{\mathrm{a}} + F_0 \cdot \left[sq_{ni}^{\mathrm{b}} - sq_{ni}^{\mathrm{c}} \right] \tag{57}$$

where F_0 represents the scaling factor. The scaling factor is utilized to adjust the magnitude of the difference vector, allowing for controlled search steps.

The crossover operator is executed following the differential mutation operator. Using the generated sequence vsq_{ni} and an original sequence sq_{ni}, we obtain the crossover population. Let usq_{ni} denote the sequence contained by the kth individual in the population after applying the mutation operator. The calculation method for usq_{ni} is presented in Eq (58).

$$usq_{ni} = \begin{cases} vsq_{ni}, & \text{if } rand(0,1) \leq CR_0, \\ sq_{ni}, & \text{otherwise.} \end{cases} \tag{58}$$

where $rand(0,1)$ represents a random real number between 0 and 1, and $CR_0 \in [0,1]$ represents the crossover probability, which is a predetermined parameter.

Note that some gene points in sequence usq_{ni} may be out of bounds and require repair operations. For each usq_{n1}, we recode it based on the sequence number of each element in ascending order. For example, if a sequence $usq_{n1}=\{3\ 0\ -1\ 9\ 7\ 4\ 8\ 6\}$ has an out-of-bounds problem, then the number 3 in the first gene point, being the 6th largest element in sequence usq_{n1}, is modified to '6', and other gene points are adjusted similarly. Thus, the modified sequence becomes $usq_{n1}=\{6\ 7\ 8\ 1\ 3\ 5\ 2\ 4\}$. For $usq_{n2} \sim usq_{n4}$, if the value of a gene point exceeds 1 (or is less than 0), it is set to 1 (or 0). Non-integer numbers are adjusted using rounding principles. After applying the aforementioned operator, a gene repair operation is also performed for infeasible solutions based on the technique proposed by Chen et al. [64].

Finally, the selection operator is performed, where the fitness values of individual $usq=(usq_n)$ and individual $sq=(sq_n)$ are calculated, and a superior individual is selected to enter the new population.

5.5. Termination conditions of iteration

We design 3 iteration termination conditions for the algorithm for LSANDA. The iteration terminates once any condition is triggered. The detailed termination rules are shown as follows:

1) The upper limit of the number of iterations is determined to acquire a solution within a finite time. We let in_{up} denote the upper limit and set $in_{\text{up}}=500$ here. When the number of iterations exceeds 500, the iteration is terminated.

2) Let $fit_{\max}$ and fit_{avg} denote the maximum and average values of a population, respectively, in the iterative process. We define $fit_{\text{dif}}=\frac{fit_{\max}-fit_{\text{avg}}}{fit_{\max}}\times 100\%$ and set a predetermined number, $\varepsilon=0.5\%$. When $fit_{\text{dif}} \le \varepsilon$, the iteration is terminated.

3) We record the time of the unimproved optimal fitness of the population θ. θ is set as 200 in this paper. When $\theta \ge 200$, the iteration is terminated.

6. Numerical experiments

Based on an actual shipping network throughout Asia and Western Europe, we conduct numerical experiments in this section to evaluate the validity of the established model and the presented algorithm. We first introduce the parameter settings in Section 6.1 and then conduct sensitivity analysis in the subsequent sections.

6.1. Parameter determination

The port data are obtained from the operating data disclosed by the China CASCO Shipping Group. There are 11 candidate ports in the experiment, as shown in Figure 5. For convenience, the abbreviations of the candidate ports are used, as shown in Table 3.

According to Cheng and Wang [43], the planning period is set at a year and can be divided into three sub-planning periods according to market conditions, namely, the normal period (Period 1, from January to April), the off-period (Period 2, from May to August) and the peak period (Period 3, from September to December), with each period lasting 120 days. The distance between two ports, the freight rates and the shipping demand between two ports come from the China CASCO Shipping

Group database and our surveys. Demand data for each planning period are fine-tuned based on the China containerized freight index (CCFI) in 2021. In terms of coding, we set each member to operate one route in the region. By adjusting the length of coding, the above assumption can also be relaxed. Although we assumed in Section 5.3 that there are only two liner companies, our model still works when the alliance contains more than two members. The size of all liners is the same, and the capacity of a container ship is 12,000 TEU. The calling frequency is set to 4 times/week. The sailing speed is 18 nautical miles/h [65]. The price of fossil fuel β is 300 USD/ton in Constraint (11) according to Cheng and Wang [43]. The settings of the other parameters are the same as in Liu et al. [6] and Gao et al. [27].

Table 3. Abbreviations of candidate ports.

No.	Abbreviation	Full name
1	TJ (China)	Tianjin Port, Tianjin, China
2	DL (China)	Dalian Port, Dalian, Liaoning, China
3	QD (China)	Qingdao Port, Qingdao, Shandong, China
4	SH (China)	Shanghai Port, Shanghai, China
5	KAO (China)	Kaohsiung Port, Taiwan, China
6	PUS (South Korea)	Pusan Port, Pusan, South Korea
7	HKT (Japan)	Hakata Port, Kyushu, Japan
8	TKY (Japan)	Tokyo Port, Tokyo, Japan
9	LEH (France)	Le Havre Port, Le Havre, France
10	FE (England)	Felixstowe Port, Felixstowe, England
11	HAM (Germany)	Hamburg Port, Hamburg, Germany

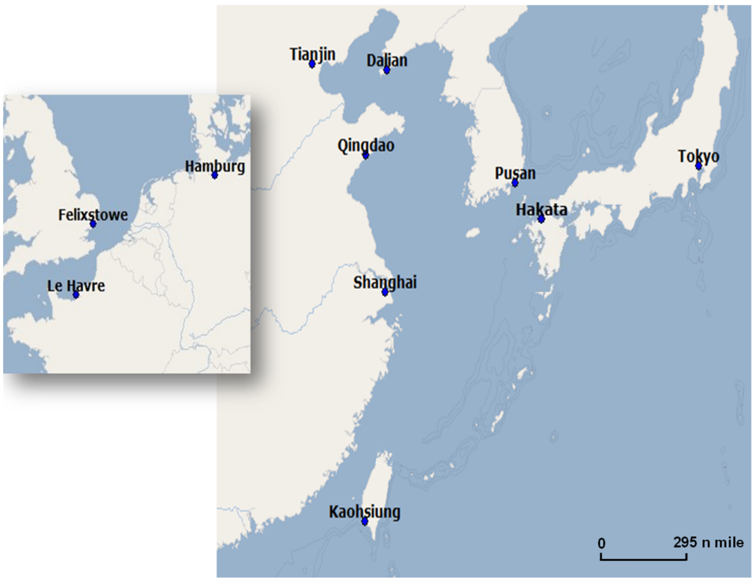

Figure 5. The candidate ports and their positions.

Finally, we set the maximum number of iterations of LSANDA as 500, while the population size is 200. More detailed parameter settings for the termination conditions can be found in Section 5.4. The roulette selection method is used to perform selection operations, and the probabilities of crossover and mutation are set to 0.9 and 0.1 according to our preliminary experiments.

6.2. Sensitivity analysis of transportation demand

We conduct a sensitivity analysis in this section to research the relationship between the transportation demand and the SNDS of a liner alliance. We fix the shipping demand of company B and adjust the shipping demand of company A to 120% and 140% of the benchmark (with initial transportation demand at 100%) to observe the changes in the liner shipping network. These three scenarios are abbreviated as D1 to D3 here. The shipping networks of a liner alliance formed by liner companies A and B for 3 scenarios are presented in Table 4.

Table 4. Calculation results under various shipping demands.

Scenario	Period	Shipping network A: alliance member A B: alliance member B	Shipping volume (TEU/week)	Freight income ($\times10^7$ USD)	Total profit ($\times10^8$ USD/year)
D1	1	A: 5-3-2-4-9-10-8-4-3-5 B: 4-11-7-2-6-3-4	42,340	2.7674	1.2153
	2	A: 5-10-11-2-4-6-8-5 B: 3-4-7-2-3	15,677	−1.4326	
	3	A: 5-10-9-3-8-7-11-10-6-5 B: 1-7-3-9-10-7-2-1	53,490	15.9755	
D2	1	A: 7-9-4-2-5-11-3-6-10-7 B: 5-6-3-1-7-6-2-4-5	41,860	2.7720	1.3790
	2	A: 6-5-1-4-3-7-2-6 B: 8-7-3-9-11-3-4-1-5-8	17,440	−1.4933	
	3	A: 3-7-6-5-4-2-3 B: 3-1-9-11-6-7-11-10-3	58,127	17.2980	
D3	1	A: 6-4-1-5-7-9-11-10-3-1 B: 2-10-11-9-5-2	45,790	2.9198	1.5735
	2	A: 4-1-5-6-4-3-7-1 B: 2-9-11-10-5-2	19,200	−1.4938	
	3	A: 1-4-3-6-4-2-1 B: 7-5-11-9-10-5-4-7	63,390	17.4903	

The shipping network for each scenario contains 6 shipping routes distributed in three stages. For scenario D1, the liner alliance network across the whole planning period contains two shipping routes operated by alliance members A and B. The shipping volume of the alliance reaches 42,340 TEU/week, while this number dropped to 15,677 USD/week in the second period. Meanwhile, the profit of the liner alliance also dropped from 2.7674×10^7 USD/year in the first stage to -1.4326×10^7 USD/year in the second stage. The network structure of each liner in the liner alliance also reflects the seasonal characteristics. For example, the structure of liner routes tends to be simpler during the off-season. By adapting the liner shipping network, liner companies can focus on serving those customers that need to be maintained. When the peak season enters, liner companies can obtain more orders from such customers and thus achieve high revenue.

The above phenomenon is in line with our expectation. In the pre-experiment estimates, the liner alliance may be operating at a loss during the off-season (the second planning period). In the last planning period, the liner alliance turns losses into profits and eventually becomes profitable.

Therefore, dividing a year into several periods and making targeted adjustments to the shipping network to maximize the overall revenue is an effective way to improve the efficiency and reduce the transportation cost of liner alliances. If a single network is used to cope with different periods of transportation demand, it will inevitably lead to misallocation and waste of resources, resulting in unnecessary losses.

6.3. Sensitivity analysis of container freight rates

This subsection conducts a sensitivity analysis to examine the fluctuation of freight rates on the shipping network of the liner alliance. We conduct three scenarios, namely, F1, F2 and F3. The latter two are obtained by setting the freight rates of the O-D pairs to 120 and 140%, respectively, based on the benchmark (scenario F1). The shipping networks of a liner alliance formed by liner companies A and B for 3 scenarios are presented in Table 5. In general, with an increase in freight rates, the revenue of the liner alliance increases significantly. It is obvious that when the freight rate rises, more profit can be obtained when transporting the same amount of cargo. The alliance members naturally benefit with more profits most of the time.

Table 5. Calculation results under various freight rates.

Scenario	Period	Shipping network A: alliance member A B: alliance member B	Shipping volume (TEU/week)	Freight income ($\times10^7$ USD)	Total profit ($\times10^8$ USD/year)
F1 (D1)	1	A: 5-3-2-4-9-10-8-1-4-5 B: 4-11-7-2-6-2-3-5-4	42,340	2.7674	1.2153
	2	A: 5-7-10-11-2-4-6-7-5 B: 3-4-7-3	15,677	−1.4326	
	3	A: 5-10-9-3-4-8-7-11-10-5 B: 1-7-3-9-10-3-2-1	53,490	15.9755	
F2	1	A: 3-2-1-6-9-10-11-8-7-3 B: 4-1-5-2-3-5-4	43,350	2.8350	1.4078
	2	A: 10-9-11-2-4-11-9 B: 1-7-5-8-6-3-4-7-1	19,663	−1.5476	
	3	A: 3-4-6-1-7-5-4-3 B: 5-8-2-7-9-10-11-3-2-5	63,450	17.6743	
F3	1	A: 4-3-7-2-5-4 B: 6-11-9-10-7-6	35,330	2.6788	1.4729
	2	A: 6-8-4-2-3-6 B: 7-5-11-10-9-5-7	15,398	−1.4298	
	3	A: 4-5-1-7-10-11-5-4 B: 2-3-7-6-1-2	52,785	17.7965	

As the freight rate increases, the shipping network of the liner alliance also shows some regular changes. On the one hand, with the growth of freight rates, the network structure of each member of the liner alliance has become more streamlined. This is because when freight rates are at a high level, high profitability can be achieved with a small number of port calls to meet orders. On the other hand, the two liner companies also achieve increased profits through a rational division of labor. For example, liner company B starts to focus only on short-distance transportation in the East Asian region, while company A is dedicated to long-distance transcontinental transport service. The liner alliance has improved the utilization rate of capacity through the division of labor by routes. Overall, fluctuations in freight rates have a significant impact on the shipping network of liner alliances.

6.4. Managerial insights

Individual liner companies usually have weak anti-risk capabilities. Especially in the off-season of international trade and ocean shipping, liner companies often cannot make ends meet. However, if a liner company terminates transportation services during the off-season, even without accounting for asset depreciation and other fixed costs, the liner company might lose numerous long-term customers. Compared with liner companies working alone, liner alliances have stronger capacity, stronger bargaining power and lower costs. Therefore, the liner alliance can provide stable ocean shipping services, thereby enhancing the elasticity of the shipping supply chain. However, this also increases the difficulty of shipping network design. According to the numerical experimental results, we present managerial insights for the alliance when designing its shipping network.

First, the shipping network adjusts structurally with changes in transportation demand. Changes in transportation demand may be due to seasonal changes in international trade and ocean shipping or may be caused by the choice inertia of shippers. The initial transportation demand affects the transportation demand in subsequent periods by affecting the shipping network of the liner alliance in the first period. In general, increasing transportation demand can increase the profits of the liner alliance. However, this quantitative relationship is not linear. The increase in the profits of the alliance may harm the interests of some of its members in a certain subperiod. However, in the whole planning period, an increasing shipping demand can increase the profits for any member. Therefore, to maximize the profits across the whole planning period, the liner alliance should design the shipping network, slot allocation scheme and empty container allocation scheme from the perspective of the whole planning period.

Second, fluctuations in freight rates influence the shipping network of the liner alliance. On the one hand, increasing freight rates can lure the alliance to improve the service frequency if the added revenue can cover the cost of the added liners. On the other hand, rising freight rates increase transportation revenue. The liner alliance calls at more ports if the increased revenue exceeds the new operating costs and port costs. Therefore, the liner alliance should always pay attention to the fluctuation of freight rates in the shipping market and adjust the liner shipping network in a timely manner. At a time when world trade is affected by uncertain events (e.g., economic crisis, geopolitics, COVID-19 epidemic), liner alliance SNDS is an effective tool to promote the resilience and sustainable development of the shipping industry.

7. Concluding remarks

The demand and supply of transportation services are uncertain due to factors such as international trade instability and unforeseen events such as economic crises, geopolitics and the COVID-19 pandemic. In response to these challenges, liner companies have increasingly formed alliances to mitigate risks and optimize capacity resource utilization. Furthermore, efficient management of empty containers as carriers for cargo transportation has gained importance. When liner companies form alliances, shipping network design becomes a collective endeavor rather than an individual pursuit. The decisions made by each member significantly impact the overall operations of the alliance. Hence, a holistic perspective that considers the resources and requirements of all alliance members is crucial for effective shipping network design. Additionally, shippers tend to exhibit choice inertia when selecting ocean shipping service providers, seeking stable services in uncertain markets. Motivated by these factors, this paper addresses the liner alliance shipping network design problem, considering shippers' choice inertia and empty container relocation. A bilevel programming model is developed to optimize the shipping network scheme and maximize the alliance's profit over the planning period. The model is transformed into a two-stage formulation and solved using a designed differential evolutionary algorithm. Sensitivity analyses are conducted to examine transportation demand and freight rates. Based on our numerical experimental results, we can reach the following conclusions.

1) Shipping network design becomes a collective responsibility once multiple liner companies form an alliance, and decisions made by each company influence the others. To maximize both the alliance's net profit and the individual liner company's profit, a comprehensive perspective is necessary for designing the shipping network and making operational decisions.

2) The profitability of a liner alliance is closely tied to its shipping network, which is influenced by shipping demand and freight rates. The alliance should proactively adjust its shipping networks in response to changes in demand and fluctuations in rates, including modifications to ports of call, calling sequences, transportation schemes and service frequencies.

3) The choice inertia of shippers determines the stability of the transportation demand of the liner alliance to a certain extent. The stability of transportation demand helps the sustainable development of the alliance. Therefore, the liner alliance should provide stable transportation services to obtain more long-term benefits.

4) Considering the impact of global economic and political uncertainties, such as geopolitical factors and the COVID-19 epidemic, liner companies must form alliances to prevent incidents such as the bankruptcy of HANJIN. Through alliance collaboration, all capacity resources and transportation demand can be integrated to design a resilient shipping network. To ensure the alliance's stable development, harmonious cooperation with shippers and a fair profit distribution mechanism are essential.

Overall, our research provides an effective reference for liner alliances to design shipping networks and allocate profits. However, our work still has some limitations and needs to be expanded for more in-depth research. First, transportation services often have strong time validity constraints that are not considered in this paper. Incorporating uncertainty such as time window factors into shipping network design is a direction worthy of research. Second, liners in shipping networks often include multiple sizes and types. Future research should fully consider the specificity of liners. Finally, how to reasonably formulate the relocation scheme of empty containers in liner alliances is a potential research direction.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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