sustainability

Article

Liner Shipping Fleet Deployment with Sustainable Collaborative Transportation

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Abstract: Facing sharp competition in the market for shipping companies, it is necessary to make reasonable and efficient decisions to optimize the container shipping line network so as to improve the shipping efficiency and reduce the transportation cost, as well as to realize the transportation sustainability. Therefore, the liner ship fleet deployment problem with collaborative transportation is proposed in this paper. This problem is formulated as a mixed-integer linear programming model that takes collaborative transportation into consideration. The model includes fixed cost, variable cost, berth cost, transport cost, penalty, compensation cost, and so on. To achieve the sustainable development of collaborative transportation, the shipping companies could make a selection between the internal routes and the external routes to serve each task by comparing the distance between the above routes. A real Asia-Europe-Oceania numerical experiment shows that the proposed sustainable collaborative transportation model can be efficiently solved by C++ calling ILOG CPLEX. Results demonstrate that the optimized shipping line network with sustainable collaborative transportation can improve the service efficiency, as well as the service level of shipping companies.

Keywords: container shipping line network; collaborative transportation; fleet deployment; sustainability

1. Introduction

Since early 2000, the actual demand of global container transportation was lower than the expected value, and the competition among liner shipping companies has become increasingly fierce. In addition, with the structural change of container liner transportation routes, the intensified market of shipping routines and the rising prices of input factors, cost control becomes exceptionally important for liner shipping companies [1,2]. In other words, the precision and efficiency of transportation service will be the crucial indicators for liner shipping companies in the foreseeable future. Therefore, in order to reduce the transportation cost for shipping companies, it is urgent for us to conduct research on the fleet deployment optimization for container liner shipping.

In this context, the optimization of the container shipping line network becomes the priority, because it is the key element for improving the shipping efficiency and controlling transportation cost. Once the routes of container liners have been designated, they cannot be changed during a certain period. Therefore, the initial decisions are of utmost importance. The decisions can be made by experience when operating a small number of ships. However, with the expansion of fleets, the decision-making process would become more complicated, and the traditional ways do not work any more. Therefore, it is necessary to adopt scientific operational research methods aimed at solving optimization problems, so as to provide references for planning and administrative decisions on the fleet deployment for liner shipping.

This article puts forward the problem of sustainable container liner shipping with collaboration transportation and solves the problems of order allocation and liner shipping deployment. A mixed integer linear programming model is constructed, and C++ calling ILOG CPLEX is used to solve the real transportation cases.

The rest of this paper can be organized as follows. Section 2 gives the literature review. Section 3 provides the problem description. A mixed integer linear programming model is developed in Section 4. Computational experiments are tested in Section 5, which are based on the real cases. Ultimate conclusions are made in Section 6.

2. Literature Review

Among the methods, such as the SWOT analysis, index tree method, mathematic programming, *etc.*, mathematic programming is the most commonly-used method in the study of container transportation optimization.

Rana and Vickson first obtained the best container shipping route by using a mixed-integer non-linear programming model [3,4]. By using the linear programming model, Perakis and Jaramillo solved the shipping scheduling problem to a certain degree [5]. Based on the mixed integer model of the previous studies, Cho and Perakis adopted the advanced mathematical planning model to design trade lanes of container liner shipping [6]. Thereafter, the proposed mathematical planning models of container liner shipping have been continuously optimized according to the actual operational situations. Agarwal and Ergun proposed a model for liner shipping network design under the constraints of cargo routing that ignores transshipment and tested three algorithms in the paper [7,8]. Alvarez extended this problem by considering the transshipment costs and increasing the problem scale [9]. Meng and Wang considered various factors and introduced a dynamic programming model based on different scenarios and mixed integer programming mathematical model, studied multi-stage fleet routing planning issues and proposed methods for further optimization of container transshipment, vessel speed programming and maritime transport timetables affected by some uncertain factors [10–12]. Gelareh *et al.* proposed a mixed integer programming model for liner shipping hub network design under a competitive condition [13]. Gelareh and Pisinger developed a model that simultaneously considers factors, including network design, fleet deployment and hub location of liner shipping companies [14]. In addition, Gelareh *et al.* developed a string planning of liner shipping that considers a hub-and-spoke network design and fleet deployment [15]. Brouer *et al.* proposed mathematical programming using a heuristic method for the liner shipping network design [16]. Brouer *et al.* proposed a base integer programming model for the liner shipping network design [17]. Plum *et al.* presented a liner shipping network design model with the service flow model [18]. Zheng *et al.* proposed a hub-and-spoke shipping network design model with the consideration of maritime cabotage legislations [19]. Mulder and Dekker proposed an integrated model that considers problems, including fleet design, scheduling and routing [20]. Lin and Tsai proposed the daily maritime liner shipping model and combined Lagrangian relaxation and local search to solve the proposed model [21]. Wang *et al.* proposed a methodology for segment-based alteration for container liner shipping network design [22]. Song *et al.* proposed a multi-objective optimization model for the liner shipping design problem [23]. Wang and Meng proposed a liner shipping network model that takes refueling of the bunker into consideration [24]. Karsten *et al.* presented a multi-commodity network flow problem and applied it in the liner shipping network design under a time restraint [25].

Based on the literature review, we can find that more actual operation issues of container liner transportation have been taken into account in the model construction. However, the impacts of transportation demand on transportation optimization were seldom considered. The following situations might happen during the actual container liner shipping process: (1) the transport capacity of container liner service providers might exceed the demand of customers; (2) the demand of customers might be larger than the transport capacity of container liner service providers; (3) container liner service providers might receive booking orders that are out of their trade lanes, and thus, this would bring about high-cost problems.

Meng and Wang conducted research on issues of container transshipment programming. In their study, they considered a situation in which the actual container transport volume of a trade lane might be higher or lower than the shipping liner on board container volume and pointed out that the booking orders should be self-running or outsourced to other service providers on the market, so as to improve the imbalance between supply and demand at a certain level [26–29]. Especially, in the actual operational process, container shipping service providers might receive a variety of booking orders, which might be away from or beyond their self-running trade lanes. Therefore, how does one reasonably allocate/assign liner scheduling resources based on transportation demands among liner carriers, which is of great significance, but has not been comprehensively discussed so far?

As a rising logistics pattern in recent years, transportation collaboration, which allows for the collaboration among relatively independent shipping companies, helps to reduce the operational cost and improve shipping efficiency by effectively decreasing empty transportation [30–34]. Studies from Ergun, Kuyzu and Savelsbergh proposed the concept of collaborative logistics and developed several solution algorithms for this problem [35–38]. Liu *et al.* used two-phase heuristic methods and a cultural genetic method to fix the booking selection assignments and routing arrangement of land transportation collaboration [39]. Hernández *et al.* proposed the single dynamic carrier collaboration planning and location model [40,41]. Özener and Ergun developed a cost allocation mechanism in collaborative transportation [42]. Lim *et al.* proposed an integer programming model for transportation procurement [43]. Audy *et al.* developed a methodology of sharing benefits among different companies for collaborative transportation through a case study of the furniture industry [44]. Chan and Zhang used a simulation methodology to evaluate the impact of collaborative transportation [45]. Dai and Chen developed three profit allocation mechanisms for the carrier collaboration problem [46]. Lozano *et al.* employed a cooperative game theory to allocate benefits for different transportation companies [47]. Wang and Kopfer proposed collaborative transportation planning of carriers and conducted the empirical analysis [48]. Dao *et al.* proposed a model of partner selection and collaborative transportation scheduling and employed GA to obtain the optimal solution [49]. Li *et al.* developed a request selection and exchange model for carrier collaboration and discussed four profit allocation strategies [50]. Zhou *et al.* proposed two collaboration modes and used a simulation methodology to obtain the optimal dispatching plan for shippers [51]. In addition, although several papers mentioned the conception of liner alliances [52–55], few studies proposed how to proceed with the shipping collaborative transportation [56–60]. Although Agarwal and Ergun designed a shipping service and provided the collaborative mechanism, the model is hard to practically apply due to its complexity. Therefore, this article further deals with the problem of container liner shipping in collaborative transportation to realize the economic sustainability by using a more applicable and simpler method [61,62]. As usual, traditional container liner shipping is mainly independently carried out by the container liners' suppliers. The order requests will be inevitably more or less than the transportation capacities of service suppliers. Therefore, the sustainable collaborative transportation of different container liners' shipping service suppliers can effectively solve the problems of imbalanced distributions of order requests and the liner deployment, so as to decrease the rate of empty transportation and increase the transportation efficiency accordingly.

The main contributions of this paper can be summarized as the following two aspects. On the one hand, although there are several works in the literature on collaborative land transportation, studies on maritime collaborative transportation with liner shipping fleet deployment are still scarce. For example, although Agarwal and Ergun studied the network design for cargo routing and collaborative mechanism in liner shipping [8,38], the transshipment cost was ignored in their study. In this paper, we conducted research on the problem of liner shipping fleet deployment for the sustainable container liner shipping network design with collaborative transportation by introducing many practical factors (transshipment, the mechanisms of penalty and compensation among shipping lines with collaboration). For achieving the sustainable development of collaborative transportation, the reasonable collaborative allocation mechanism of transportation demands among liner carriers was obtained by comparing their distances between the internal routes and the external routes. The maritime collaborative transportation problem can be simplified so as to obtain sufficient applications by shipping liner companies. On the other hand, a mixed-integer linear programming model was constructed considering many actual constraints. A real case study of the Asia-Europe-Oceania liner shipping was used to validate the proposed model and methodology. Especially, C++ calling ILOG CPLEX is used as a solver for this proposed model with a mass of decision variables. Results demonstrate that the optimized shipping liner network with sustainable collaborative transportation can be solved efficiently, which can improve the service efficiency, reduce the cost, as well as improve the service level of shipping companies.

3. Problem Description

3.1. Liner Shipping Route of Traditional Transportation

Suppose "I" is one port of shipping routes, which belongs to set "I", and the port calling sequence is regarded as a ship route. "I" represents a set of ports of a certain route. Suppose "R" is a set of liner shipping company's routes and that the certain shipping route "r" belongs to set "R". Every shipping route should be considered as a closed loop circuit, and the time that a liner runs along the route is about one week.

For a particular ship route "*r*" where the shipping route belongs to set "R", the port calling sequence can be expressed as follows:

$i_{r1} \rightarrow i_{r2} \rightarrow \cdots \rightarrow i_{rN_r} \rightarrow i_{r1}$, where N_r is the number of ports called on the itinerary.

For example, if a liner (ship) called in Sokhna, Aqabah, Jeddah, Salalah, Karachi, Jebel Ali, Salalah and Karachi (shown below) and returns to Sokhna finally, the route can be expressed as follows (shown in Figure 1):

$$\text{Sokhna} \rightarrow \text{Aqabah} \rightarrow \text{Jeddah} \rightarrow \text{Salalah} \rightarrow \text{Karachi} \rightarrow \text{Jebel Ali} \rightarrow \text{Salalah} \rightarrow \text{Karachi} \rightarrow \text{Sokhna}$$

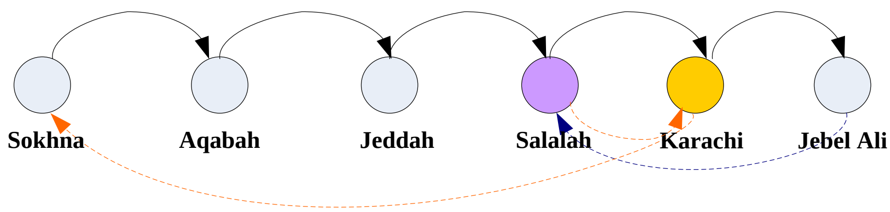

Figure 1. Sequence of ports of call.

3.2. Liner Shipping Route with Collaborative Transportation

The above routes indicate that the vessel needs to go through Salalah repeatedly, and the cost will inevitably pile up in that situation. In this context, we take container liner shipping routes with collaborative transportation into consideration (shown in Figure 2). Since the order is already known, we could optimize the problems regarding the liner shipping deployment of order distribution between the inside and outside shipping lines by estimating the distance and cost between two ports. Then, we could achieve the objectives, including decreasing the rate of empty transportation, reducing transportation cost and improving operational efficiency. All of the above problems will be solved in the next section.

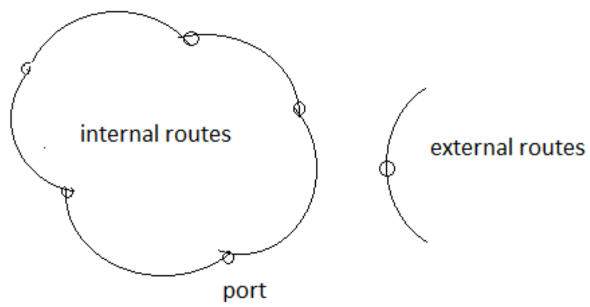

Figure 2. Liner shipping route with collaborative transportation.

4. Model Formulation

In order to describe the above problems in detail, we formulate a mixed integer programming model for the problem of the container liner shipping network design with collaborative transportation in the following parts. The assumptions, the notation on sets, parameters and decision variables are illustrated in the following subsections.

4.1. Assumptions

(1) We assume that the hub ports and the ship routes are given in advance.
(2) We suppose that the demand is fixed.
(3) In order to take collaborative transportation into consideration, we assume that ships can be transported at any ports.
(4) In collaborative transportation, we assume that there would be no empty containers.
(5) Finally, we make a selection between the internal routes and the external routes to serve each task by comparing the distances, as well as costs between the above routes in collaborative transportation.

4.2. Decision Variables

The decision variables of the proposed model can be specified as follows:

x_{rv}: A binary variable, which is equal to one if ship route $r \in R$ was deployed with a private ship of type V, $v \in V$.

z_i: If port i is assigned to an external ship, $z_i = 1$; if else, $z_i = 0$; $i \in I$.

$\hat{N}_{or}^{tran}$: The number of containers (twenty feet equivalent units per week, TEUs/week) discharged at port o on ship route r, $r \in R$

$\tilde{N}_{or}^{tran}$: The number of containers (TEUs/week) loaded at port o on ship route r, $r \in R$.

d_{pi}: The number of containers originating from port i.

d_{op}: The number of containers destined for port i.

m_r: The number of ships deployed on the ship route r.

4.3. Parameters

p_i: The penalty cost of port i ($i \in I'$) when the order is assigned to an external carrier.

q_i: The compensative cost of port i ($i \in I'$), which represents the order outsourced by other carriers, will be transported by the inside shipping lines.

h_i: The upper bound on the travel distance of a private ship upon leaving the port i, $i \in I$.

h_d: The minimal distance of each ship.

h_j: The upper bound on the travel distance of a private ship upon leaving the port j, $j \in J$.

H: The maximal distance of each ship.

l_{ij}: The travel distance equals the distance from end port i of the first arc to the starting port j of the second arc plus the distance of the second arc.

l_{id}: The travel distance equals the distance from the end port i of the first arc to the starting port d of the second arc plus the distance of the second arc.

$x_{rv}{}'$: A binary variable, which is equal to one if ship arc l_{id} is deployed with a private ship of type $v, v \in V$.

M: A big positive number.

c_{rv}^{var}: The variable cost of a ship on the route $i, i \in I$.

c_{rv}^{fix}: The fixed cost of a ship on the route $i, i \in I$.

c_{rv}^{ber}: The price of berth.

t_{or}: The berth time of ship $v, v \in V$.

c_i: The transport cost of containers.

$\hat{c}_o$: The cost of discharge.

$\tilde{c}_d$: The cost of loading.

Cap_v: The container capacity (twenty feet equivalent units, TEUs) of a ship of type $v, v \in V$.

f_{ri}^{o}: The number of containers (TEUs/week) originating from port o and stowed on board ships sailing on the leg i of ship route $r, r \in R$.

τ_{rv}^{fix}: The fixed portion of the time (hours) for the round-trip if service route $r, r \in R$ is deployed with a ship of type $v, v \in V$. τ_{rv}^{fix} includes the sailing time and standby time for pilotage in and out at all of the ports.

d_{od}: The sum of loaded and discharged containers at port o on ship route $r, r \in R$.

V: Types of ships; R: internal routes; R': external routes; I: ports on route $r, r \in R$.

I': Ports on external routes $r', r' \in R'$.

4.4. Objective Function

$$\begin{aligned}\min \sum_{r\in R}\sum_{v\in V} c_{rv}^{fix} x_{rv} + \sum_{r\in R}\sum_{v\in V} c_{rv}^{\text{var}} x_{rv} + \sum_{r\in R}\sum_{v\in V}\sum_{o\in I} c_{p_{ri}v}^{ber} t_{ov} x_{rv} (\hat{N}_{or}^{tran} + \tilde{N}_{or}^{tran}) \\ + \frac{1}{2} c_i \times \left[\sum_{r\in R}\sum_{o\in I} \left(\hat{N}_{or}^{tran} + \tilde{N}_{or}^{tran} \right) - \sum_{i\in I} d_{pi} - \sum_{o\in I} d_{op} \right] \\ + \sum_{o\in i}\sum_{d\in i} (\hat{c}_o + \tilde{c}_d) d_{od} + \sum_{i\in I'} p_i z_i - \sum_{i\in I'} q_i (1 - z_i)\end{aligned} \tag{1}$$

We refer to this model as Question 1 (Q1). The total transportation cost is the objective function that needs to be minimized.

Equation (1) has seven terms: the first term is "the total fixed cost"; the second term is "the total variable cost"; the third term is "the total berth occupancy charge"; the fourth term is "the total transshipment cost"; the fifth term is "the total loading and discharge cost"; and the last two terms represent "the penalty cost" and "compensative payments received from external shipping lines", respectively.

Model Q1, a mixed integer programming model that solves a container collaborative transportation problem, is subject to the following constraints in Section 4.5.

4.5. Constraints

$$z_i + x_{rv} = 1 \tag{2}$$

$$h_d = 0 \tag{3}$$

$$h_i + l_{ij} - (1 - x_{rv})M \leqslant h_j, \forall i \in I, r \in R, v \in V, j \in J, i \neq j \tag{4}$$

$$h_i + l_{id} - (1 - x_{rv}{}')M \leqslant H, \forall i \in I', r \in R, v \in V \tag{5}$$

$$0 \leqslant h_i \leqslant H; \forall i \in I \tag{6}$$

$$168m_r \geqslant \sum_{v\in V} x_{rv}\left[\tau_{rv}^{fix} + \sum_{o\in I}\sum_{r\in R} t_{ov}\left(\hat{N}_{or}^{tran} + \tilde{N}_{or}^{tran}\right)\right] \tag{7}$$

$$\sum_{o\in I} f_{ri}^{0} - \sum_{r\in R}\sum_{v\in V} Cap_v x_{rv} \leqslant 0; \forall i \in I \tag{8}$$

$$f_{i,i-1} + \tilde{N}_{or}^{tran} = \hat{N}_{or}^{tran} + f_{ri}^{0}; \forall r \in R, \forall i \in I, \forall o \in I \tag{9}$$

$$f_{ri}^{o} = 0; \forall i \in I, o = i_{r,i+1} \tag{10}$$

$$\hat{N}_{or}^{tran} = 0; \forall r \in R, \forall i \in I, o = p_{ri} \tag{11}$$

$$\sum_{r\in R}\sum_{o\in I}\left(\hat{N}_{or}^{tran} + \tilde{N}_{or}^{tran}\right) = d_{od}; \forall d \in I, d \neq 0 \tag{12}$$

$$\hat{N}_{or}^{tran} \geqslant 0; \forall r \in R, \forall i \in I, \forall o \in I \tag{13}$$

$$\tilde{N}_{or}^{tran} \geqslant 0; \forall r \in R, \forall i \in I, \forall o \in I \tag{14}$$

$$f_{ri}^{o} \geqslant 0; \forall r \in R, \forall i \in I, \forall o \in I \tag{15}$$

$$x_{rv} \in \{0,1\}; \forall r \in R, v \in V \tag{16}$$

$$z_i \in \{0,1\}; \forall i \in I' \tag{17}$$

Constraint (2) ensures that all of the containers should be transported by internal companies and external companies.

Constraints (3)–(6) represent the sub-loop elimination and ensure that the given distance span would not be exceeded; where M stands for a big positive number.

Constraint (7) ensures that the number of ships deployed on a ship route is large enough to maintain a weekly service frequency; where 168 is the number of hours in a week.

Constraint (8) is the capacity constraint on each leg of the ship routes.

Constraint (9) and Constraint (12) enforce flow conservation at each port on each ship route.

Constraint (10) represents that containers originating from a given port *O* should not return to the same port.

Constraint (11) requires that containers should not be discharged at the given port.

Constraints (13)–(15) indicate that $\hat{N}_{or}^{tran}$, $\tilde{N}_{or}^{tran}$ and f_{ri}^{o} are non-negative.

Constraints (16)–(17) represent two binary variables.

4.6. Input and Output Parameters

The input and output parameters are listed as follows:

Input parameters:
$c_{rv}^{fix}, c_{rv}^{\text{var}}, c_{p_{ri}v}^{ber}, t_{ov}, c_i, d_{pi}, d_{op}, \hat{c}_o, \tilde{c}_d, g_i, e_i, h_i, H, Cap_v, \tau_{rv}^{fix}, M$
Output parameters:
$x_{rv}, \hat{N}_{or}^{tran}, \tilde{N}_{or}^{tran}, z_i, (d_{od}), d_{pi}, d_{op}, m_r$

5. Numerical Experimentation and Analysis

The numerical experiment is based on a mixed integer linear programming (MILP) mathematical model. Symbols of x_{rv} and z_i are variables that range from 0–1. The logical variables that range from 0–1 show whether the system is in a certain situation or which plan will be chosen during the decision-making process. This article will use C++ calling WebSphere ILOG CPLEX to obtain the estimated results of the model. The ILOG CPLEX, mathematical optimization software of the IBM WebSphere family, can transfer complex business problems to mathematical programming models. The optimization procedure of ILOG CPLEX has higher capacity for large-scale optimization.

The problems of linear programming, quadratic programming, mixed integer quadratic programming, quadratic constrained programming, mixed integer quadratic constrained programming and mixed integer linear programming can be solved by using this software. To summarize, it has an obvious advantage in settling matters regarding complicated linear programming. Meanwhile, it provides a wide variety of programming environments to interface ILOG CPLEX. This article applies VS2000 to compile C++ to solve the above MILP model in the ILOG CPLEX.

5.1. The Data Description

According to the actual situation of container shipping, we select a real Asia-Europe-Oceania shipping network of an international liner shipping company as a numerical object for test and take the 46 major ports in the Asia and Europe-Atlantic shipping network into consideration (shown in Figure 3, which has been revised based on Wang and Meng [11]). Especially, we take four testing cases with different container shipment demands. There are three types of liners (capacities of 3000TEUs, 5000TEUs and 10,000TEUs), and the relevant data are shown in Table 1 (taking Wang and Meng [11] as the reference). The average costs of loading and unloading are both 150USDs/TEU, while the process of shipping costs are 200USDs/TEU. Characteristics of the liner shipping fleet are given in Table 1. The fixed costs and sailing time of the four models are provided in advance by an international liner shipping company. In total, there are 11 shipping routes between Asia and Europe, which can be seen in Table 2 in the Asia-Europe shipping network. Each shipping route has two or three types of candidate ships. All of the parameters of shipping lines are estimated according to the historical data of some international shipping companies after modifications due to business confidentiality. This collaborative transportation problem is solved by compiling C++ calling ILOG CPLEX running on a 3.00-GHz Core PC with 4 GB of RAM.

Table 1. Characteristics of the liner shipping fleet (revised based on Wang and Meng [11]).

Type of the Ship (Twenty Feet Equivalent Units, TEUs)	3000	5000	10,000
Fixed operating cost (1,000USDs/week)	76.9	115.3	173.1
Productivity (moves/hour)	70	95	
Fixed charge ($)	12,000	20,000	
Speed (knots)	18.9	22.5	26
Bunker cost (USDs/n mile)	72	78	100
Berth occupancy charge (USDs)	1000	1666	3333
Fixed cost for calling at a port (USDs/h)	5477	7071	10,000
Fixed time when calling at a port (h)	4	4	4
Container handling time (h/TEU)	1/85	1/95	1/120

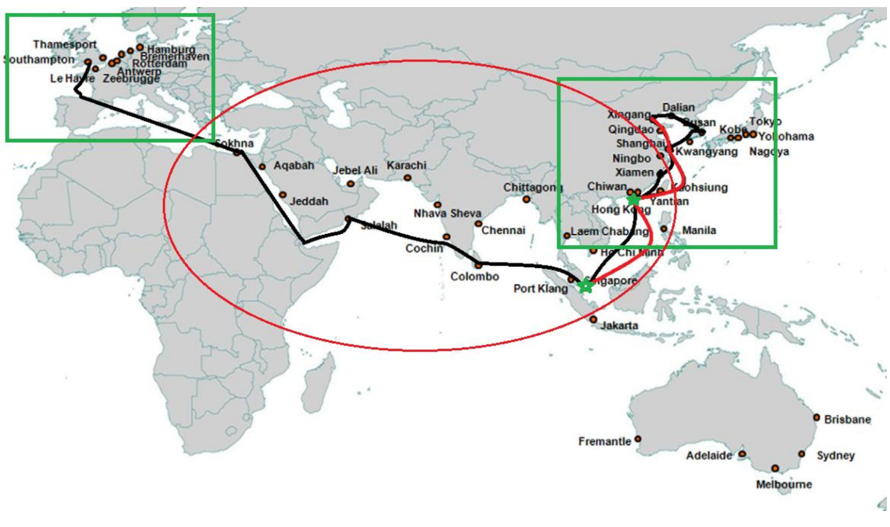

Figure 3. Asia-Europe-Oceania shipping network.

Table 2. Shipping routes.

Company	Shipping Routes
A	1. Chittagong—Chennai—Colombo—Cochin—Nhava Sheva—Cochin—Colombo—Chennai—Chittagong 2. Southampton—Thamesport—Hamburg—Bremerhaven—Rotterdam—Antwerp—Zeebrugge—Le Havre—Southampton 3. Sokhna—Aqabah—Jeddah—Salalah—Karachi—Jebel Ali—Salalah—Sokhna 4. Southampton—Sokhna—Salalah—Colombo—Singapore—Hong Kong—Xiamen—Shanghai—Busan—Dalian—Xingang—Qingdao—Shanghai—Hong Kong—Singapore
B	5. Yokohama—Tokyo—Nagoya—Kobe—Shanghai—Hong Kong—Singapore—Hong Kong—Yokohama 6. Manila—Kaohsiung—Xiamen—Hong Kong—Yantian—Chiwan—Hong Kong—Manila 7. Yantian—Hamburg—Sokhna—Jeddah—Port Klang—Singapore—Manila—Shanghai—Yantian 8. Dalian—Hong Kong—Shanghai—Qingdao—Ningbo—Shanghai—Kwangyang—Busan—Dalian
C	9. Ho Chi Minh—Laem Chabang—Singapore—Port Klang—Ho Chi Minh 10. Brisbane—Sydney—Melbourne—Adelaide—Fremantle—Colombo—Salalah—Rotterdam—Salalah—Colombo—Brisbane 11. Port Klang—Singapore—Jakarta—Kaohsiung—Busan—Kaohsiung—HongKong—Chiwan—Xingang—Port Klang—Colombo —Salalah—Southampton

5.2. The Numerical Results

In this subsection, we test the problem of container liner transportation optimization planning of Company "A" in collaborative transportation, for which liner container shipping routes of Company "A" are internal shipping lines, while liner container shipping routes of Companies "B" and "C" are external shipping lines.

The demand for container transportation between Asia and Europe is 21.42 million TEUs on the container liner shipping routes for Company A. However, due to limited transportation capacity, Company A cannot fully meet the inside and outside orders on transportation routes. We obtain the relevant results based on the numerical computation of the proposed mixed integer liner model. We can reach the perfect situation with the lowest total cost. The numerical results of collaborative transportation for Companies A, B and C on shipping routes, types of ships and trade lanes are illustrated in Table 3. Table 4 shows the comparison between the transportation demand and the actual transportation volumes on several container shipping routes.

Table 3. Results of shipping routes, types of ships and trade lanes.

Asia-Europe Shipping Line	Number of Shipping Routes	3000TEUs	5000TEUs	10,000TEUs
Company A	4	6	4	25
Company B	8	5	5	20
Company C	3	3	6	13
Total	11	14	15	58

Table 4. The comparison between the transportation demand and actual transportation volume of Company A.

Place of Departure	Destination	Transportation Demand (Ten Thousand TEUs)	The Actual Volume (Ten Thousand TEUs)
Dalian	Hong Kong	82	24
Hong Kong	Qingdao	1	0
Shanghai	Singapore	39	11
Singapore	Shanghai	1	0
Hong Kong	Xingang	3	2
Xingang	Singapore	3	0

The results show that the demand for container shipping between the ports on Company A's shipping routes is 21.42 million TEUs, while the actual service capacity of the transport operator is

20.50 million TEUs (Table 5). Therefore, the gap will be made up by external container shipping routes that belong to Companies B and C in collaborative transportation.

Table 5. The computational results.

	The Total Cost (Ten Thousand U.S. Dollars)	Total No. of Transshipment Containers	Container Transportation Volume (Million TEUs)
Quantity	2733.63	19	20.50

It can be seen from Table 5 that the total demand for the route starting from Dalian to Hong Kong is 820,000TEUs. However, the transport capacity of Company A on this shipping route is 240,000TEUs (Dalian-Xingang-Qingdao-Shanghai-Hong Kong). Therefore, according to the numerical results, the remaining demand of 580,000TEUs should be fulfilled by Company B with collaborative transportation on Shipping Route 8 (Dalian-Hong Kong). Based on the above analyses, the shipping orders of 10,000TEUs from Hong Kong to Qingdao should be transported by Company B on its Shipping Route 8 (Hong Kong-Shanghai-Qingdao). Accordingly, the remaining shipping orders of 280,000TEU from Shanghai to Singapore should be fulfilled by Company B on its Shipping Route 5 (Shanghai-Hong Kong-Singapore). Due to the limited transport capacity of Company A, all orders from Singapore to Shanghai should be transported by Company B on its Shipping Route 7 (Singapore-Manila-Shanghai). The shipping demand from Hong Kong to Xingang is 30,000TEUs, for 20,000TEUs would be transported by Company A on its own route (Hong Kong-Xiamen-Shanghai-Busan-Dalian-Xingang), and the remaining demand of 10,000TEUs would be fulfilled by Company C on its Shipping Route 11 (Hong Kong—Chiwan—Xingang) (see Figure 4).

Figure 4. The partial results of the collaborative transportation of Companies A, B and C.

5.3. Different Container Transportation Demand Analysis

In order to further validate the effectiveness of the proposed model and methodology, we generate different origin to destination (OD) pairs of 100, 200, 300, 400, 500 and 600. Each pair generates 10 instances, and the computed results are shown in Figure 5.

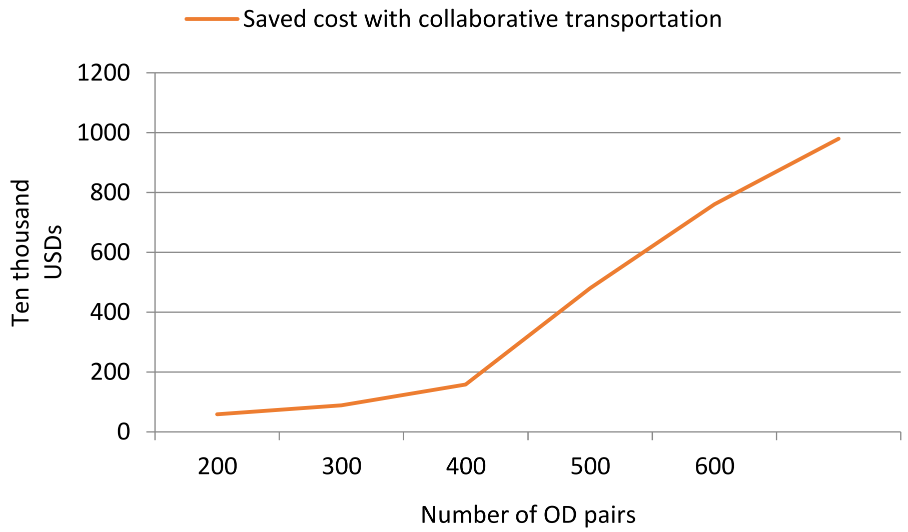

Figure 5. The relationship between origin to destination (OD) pairs and saved cost with collaborative transportation.

As shown in Figure 5, we can see that the cost saved in collaborative transportation rises with the increase in OD pairs. Especially, there would be an obvious increase when the number of OD pairs equals 400. With the increasing demand for OD pairs, the average container loading rates of Companies A, B and C would be significantly improved (see Figure 6). In addition, when OD pairs increased from 100–400, this phenomenon (cost saving) would become more obvious. The effect of collaborative transportation can be reflected, and the average container loading rate in collaborative transportation will be greatly improved. Although there are only three kinds of ships, the actual loading rate is nearly about 90% when the number of OD pairs increases to 400. Additionally, the rates of loading with shipping lines from 1–11 are shown in Figure 7. Considering that the loading rate of Shipping Line 10 is low, we suggest to arrange smaller ships for the shipping line or cancel the shipment. The above results provide valuable information to support the decision-making of global shipping liner companies.

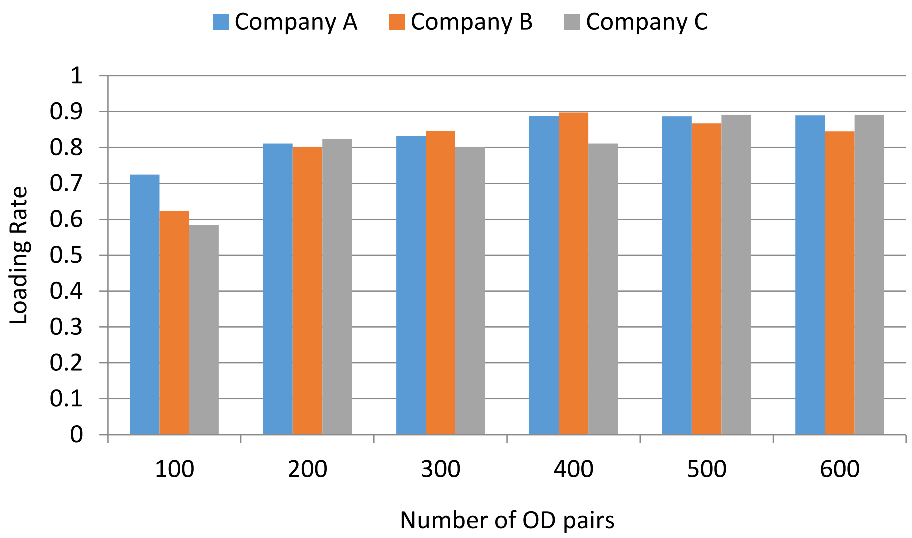

Figure 6. Loading rate of Companies A, B, C with different numbers of OD pairs.

Figure 7. Loading rate with shipping lines from 1–11.

6. Conclusions and Implications

With the structural changes of container liner shipping routes and the exacerbating of the market intensification of the routes, cost control of liner shipping companies has become increasingly difficult. Moreover, costs of other inputs also put much pressure on liner shipping companies. In this context, research on the accuracy of shipping services, the optimization of container liner shipping and cost reduction of shipping companies become more urgent. In order to reduce shipping costs and increase profits of shipping companies, this article puts forward the issue of sustainable optimization of container liner shipping in collaborative transportation. We establish a mixed-integer liner mathematical model to investigate the distribution of orders on inside and outside routes by calculating the distance between the ports. By using ILOG CPLEX in numerical experiments, the model of this paper takes fixed cost, variable cost, berthing cost, transshipment cost, penalty cost, compensative payments and other factors into account and obtains the optimal values in collaborative transportation.

However, shortcomings still exist in this research. For example, the model is based on the premise that the demand of each port is fixed; however, in the actual situation, the demand for container transportation changes with time. Additionally, the assumed routes given in the article are the optimal solutions in the collaborative transportation based on the fixed container liner shipping routes; however, the existing liner container shipping routes are not necessarily the optimal routes under collaborative transportation.

Maritime transportation is the most widely-used method for international shipment of goods; therefore, the optimization of container liner shipping is an important issue in the field of sustainable maritime trade. On the tactical level, the sustainable optimization of liner container transportation includes research of scheduling, the design of the route network, the design of the liner planning and sailing speed. Hence, the optimization of liner container transportation on the tactical level deserves further research.

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