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Research on strategic liner ship fleet planning with regard to hub-and-spoke network

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Abstract
In order to obtain the biggest economic benefits, large shipping firms widely use hub-and-spoke network to operate ships. The reasonable shipping network not only decreases the cost of infrastructure construction to achieve scale economies, but also be efficient to allocate the existing resources of maritime business. Shipping firms usually are in pursuit of the large-scale container ship, leading some firms to blindly upgrade vessels and cause the loss of profit. Since the operating costs and transportation time is the major problem for shipping firms to get more profit, in this study, we research the relationship of route design, fleet planning and container freight to build the objective function in view of the minimization of time and cost. This study proposes the mixed integer linear programming model of hub-and-spoke network and liner ship fleet planning to choose the appropriate ship location and distribution, and applies Lagrange Heuristic Algorithm to solve the model. The simulation results verify the validity of this algorithm, showing that when firms invest the large ship, it usually gets lower freight rate, by contrast, small vessels have cost and scale advantages. But in order to cope with changes in market demand, for the operations of shipping firms, owning large vessels are still necessary. Our two-phase model considers problems comprehensively to complete the network design of liner ship fleet planning. Lagrange Heuristic Algorithm can get high quality solutions in a relatively short time, it provides reference significance for solving related problems in the future.

Keywords Hub-and-Spoke Network · Liner Shipping · Fleet Planning · Lagrange Heuristic · Operations Research

1 Introduction

China's economy is undergoing the continuous adjustment of industrial structure, the tertiary industry has become the main force of economic development (Ma et al. 2017; Jingqiao 2017). With the advancement of "the Belt and Road Initiative" strategy, the shipping demand of China develops from radiation structure to global network structure, which makes the shipping industry urgently keep up with the pace of the world economy (Zhang 2018; Chhetri et al. 2018; Wei et al. 2018; He 2020). Shipping industry drives the development of port, shipbuilding, logistics and other related marine businesses, ranking second only to Chinese tourism industry in terms of total service scale (Wan et al. 2015; Lee and Shen 2017). Although the imbalance between supply and demand has always existed since the financial crisis, the shipping supply still shows a high growth rate, and the market transport capacity is vigorous for a long time (Kim 2019). Marine transportation is a convenient and fast way for ships to transport commodity among ports of different countries or regions, more of China's import and export commodity are carried out by sea carriage.

In general, the development of shipping industry in China is not only reflected in the quantity and size, also involves the fleet planning, route design and layout (Meng et al. 2012, 2014; Baykasoğlu et al. 2019). Marine transportation, as an important guarantee for China's economic strategy of import and export channels, it is of great significance to enhance cargo transportation, improve the shipping network layout and infrastructure construction (Zhao et al. 2016; Yang et al. 2018a, b). The external market environment requires shipping firms to form alliances to provide diversified services, thus shipping alliances lead the total shipping capacity to increase continuously in the world. For example, Maersk, a top shipping group company, has occupied more than half of the shipping market with high-quality and innovative service

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(Sornn-Friese 2019). In the past, bulk cargo was the main driving force for the demand growth, with the adjustment of economic structure, the shipping demand is changing rapidly. In the current and future development of marine shipping, vessel types tend to be large, containerized and low carbonization, and the vessel containerization increasingly become the shipper's preferred transportation mode. The constant rise of the container transportation makes the shipping tend to be standardized, ensures the transportation quality, and greatly shortens the transportation time. Meanwhile, container vessels save the cost of loading and unloading, and improve the overall transportation efficiency (Reich 2012; Imai et al. 2013).

In the container liner transportation, liner service networks are the operational foundation of liner firms. With the formation of liner shipping alliances, the higher requirements are put forward for the operation network and service frequency. The past multi-port affiliate network shows its insufficiency, while a hub-and-spoke network with its advantages of combining hub ports, branch ports, trunk lines and branch lines, reducing restrictions on ports and achieving scale economies, has quickly become the main operation mode of liner shipping route network (Asgari et al. 2013). With the scale trend of large vessel, shipping firms tend blindly to pursue an increasing number of shipping capacity in order to maximize profits. However, large deadweight container vessels do not always win scale economies, but waste transportation capacity (Garza-Reyes et al. 2016). In the meantime, shipping firms need to slow down the speed of fleet operation, reduce freight rates, or adopt other measures to maintain daily profit costs. It is important for shipping firms to equip suitable vessels for specific networks while minimizing voyage time and costs. Based on the systematic literature review, we find that the hub-and-spoke network design has been widely used in logistics site selection. Each hub-and-spoke line can generate a certain transportation discount to achieve scale economy, however, for the holistic consideration of transport time and cost, existing research on the hub-spoke network and fleet planning problems is still limited. Most research focus on certain aspects, but the solution is not able to coordinate with each other in the shipping network (Gelareh and Pisinger 2011; Khorheh 2017). Furthermore, there has been little research on the combination of hub-and-spoke network, liner shipping and fleet planning.

To fill the above research gaps, this study takes the transport time and operating cost as the objective function to establish the fleet network planning model. Specifically, we aim to address the operations research gap by the Lagrange heuristic model, and put forward the Lagrangian decomposition method to obtain the lower bound of the optimal value. Since the poor constraint ability of branch-and-bound method to solve large-scale problems, small problems (i.e., n = 10) usually take a lot of time to deal with, even not always possible to get the optimal solution (Ruszczyński 1995; Tosserams et al. 2007; Necoara and Suykens 2009; Granada et al. 2012; Yang et al. 2018a, b). This study adopts the heuristic algorithm to construct feasible scheme to makes up for the research inadequacy, and provide some theoretical and practical significance.

The remainder of this paper is organized as follows. The following section reviews theoretical foundations. Then the method section describes the processes of model building and algorithm design. Next, case study results are presented and important research findings are discussed. Finally, we summarize the conclusions, and provide future research directions.

2 Theoretical foundation

This study involves the following two research directions. One is the hub-and-spoke network planning, the other is the fleet programming.

2.1 Hub-and-spoke network planning

Global liner shipping is a competitive industry, requiring liner carriers to carefully deploy their vessels efficiently to construct a cost advantage, and the aim of liner line layout is to solve the problem of service flow in the shipping network (Plum et al. 2014). Hub-and-spoke networks have recently received increased attention due to their multiple applications in public transportation, logistics distribution systems, and telecommunications (Yang et al. 2017). The hub-and-spoke paradigm has been a fundamental principle in geographic network design for more than 40 years, and such networks possess the ability to exploit scale economies of transportation by aggregating network flows (Carlsson and Jia 2013). Aykin (1994) introduced the capacitated hub-and-spoke network design problem in which hubs have limited capacity for channelling flows, also, a heuristic procedure partitioning the set of solutions are presented. Elhedhli and Hu (2005) considered a hub-and-spoke network problem with congestion, and provided a Lagrangean heuristic that finds high-quality solutions within reasonable calculation time. Taking into account the constraints of loading capacity, port construction and butterfly port factors, the mixed integer programming is applied to solve a hub-and-spoke network problem with regard to the benefit maximization (Gelareh et al. 2010). Meng and Wang (2011) develop a mathematical program with equilibrium constraints model for the intermodal hub-and-spoke network design with multiple stakeholders and multi-type containers, which is capable of reflecting the transition from scale economies to scale diseconomies in distinct flow regimes.

In recent years, the issue of the hub-and-spoke network planning has been the subject of intense research (Hu et al. 2020). Under the competition and cooperation relationship between hub ports and shipping firms, Asgari et al. (2013) mainly considered network design problem by the game theory. Lagrange decomposition and heuristic algorithm are used to solve the hub-and-spoke network problem under the environment friendly social conditions (Gelareh et al. 2013). Mulder et al. (2014) conducted the integrated problems in liner transportation, including fleet design, ship scheduling and cargo routing, and solved the network design bottleneck through the modeling algorithm of 58 test ports fromMaersk Asia-Europe routes. Zheng et al. (2015) analyzed the impact of coastal transport law on liner transport hub-and-spoke network design via a two-stage model, especially, the second stage considered the route design and ship allocation problem. In the context of Belt and Road Initiative (BRI) originally proposed by China, Wei et al. (2018) studies a logistics network connecting the inland regions by dry ports and establish a hub-and-spoke network based on a two-stage logistical gravity model. Zhalechian et al. (2018) proposed a novel decision-making framework to conduct a resilient hub network under disruption risks, and a hybrid solution approach is built to solve such a multi-facet situation.

2.2 Fleet programming

Previous research mainly focuses on fleet planning, which primarily utilize operations research and computational intelligence-based techniques (Baykasoğlu et al. 2019). Everett et al. (1972) took the bulk cargo transportation fleet of United States as the research object, systematically analyzed of the optimal fleet composition (i.e., cargo flow, ship type, investment recovery), and provided guiding opinions for the allocation decision of large fleet. Lane et al. (1987) analyzed the cost and benefit of liner fleet by generating a series of ship and route combinations manually, and then uses dynamic programming to solve multi-stage decision-making process. In view of the quadratic relationship between fuel consumption and ship speed in unit time, a nonlinear mixed integer programming model is established by combining fleet planning and speed optimization (Brown et al. 1987). Rana and Vickson (1991) carried out route configuration for multi-ports and multi-ships, applied Lagrange relaxation method to optimize the route, and established a mixed integer nonlinear programming model. Especially, Cho and Perakis (1996) leverage two optimization models for fleet planning to improve route design of container liner firms: model one is a linear programming function that pursues maximum profit on the generated route; model two is a mixed integer programming model that pursues the minimum of operating cost, idle cost and capital cost as objective functions. According to Powell and Perkins (1997), all aspects of factors should be considered comprehensively, and the mixed model of integer programming and linear programming is more suitable for fleet planning.

Overall, the main methods of strategic fleet planning include linear programming, integer programming, dynamic programming and simulation technology, among which the advantages of linear programming are fast in solution speed and convenient to apply (Franceschetti et al. 2017). Dantzig and Fulkerson (2003) chose bulk cargo as the research object, created a linear programming model integrating ship scheduling and fleet planning to achieve the optimal route programs. By using column generation algorithm and Benders decomposition method, a mixed integer programming model combined network design, ship scheduling and cargo transportation problems is constructed to maximize profits (Agarwal and Ergun 2008; Özceylan and Paksoy 2013). By reasonably changing ship speed, Wang and Meng (2012) put forward research methods for fleet planning in liner transportation, which solves the time consumption caused by uncertain events, so as to ensure that ships can maintain the stability of line operation and ship schedule. In terms of fleet planning, the number of different ship types take an impact on customer satisfaction, transportation time, and dispatching costs (Lin et al. 2010; Tamannaei and Rasti-Barzoki 2019). Since the constraint of the original generation process, the Lagrange decomposition method are proposed, which biggest advantage is the effective decision space and superiority.

3 Model building

3.1 Problem description

According to the hub-and-spoke network model, we analyze the fleet planning of liner transportation. In this paper, the hub-and-spoke network is a single distribution mode, that is, each non-spoke port can only be connected with one hub port. All cargos are transported from the initial spoke port to the destination, in which the cargos must be transported through the hub port. Hub ports are connected with each other by trunk line, and the hub ports and spoke ports are connected by branch line. In the hub-and-spoke system, the spokes are liner services between the regional terminals and hubs. At the hub, the transport units are transferred from one liner service to another connecting hub with the destination terminal. Each container cargo has two connecting ports, namely the origination and destination (OD) point. The OD transportation needs to rely on the connection of the axis and the spoke, and it can be completed through the transfer of hub ports. As shown in Fig. 1, the hub-and-spoke network aggregates port cargos from different origination and destination points on the same axis, generating scale effect, which

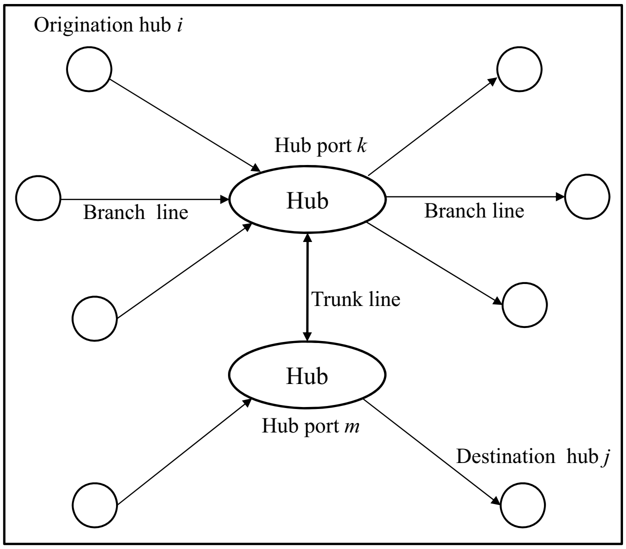

Fig. 1 The Hub- and -spoke network structure

is conducive to reducing transportation costs and improving the utilization of transportation equipment.

As shown in Fig. 1, the hub-and-spoke network G = (V, E, W) is composed of port nodes, shipping lines, and container freight volume. Port nodes are divided into hub ports and spoke ports. Hub = {k, m} represents the hub port set, spoke = {i, j} represents the spoke port, i is the origination port set, and j is the origination port set. The ship route includes the trunk line and the spoke line, B = {(k, m)/$k \in$ K, $m \in$ M} is the trunk line set, T_1 = {(i, k)/$i \in$ I, $k \in$ K} and T_2 = {(m, j)/$m \in$ M, $j \in$ J} are branch lines. The hub-and-spoke network requires direct connection between hub ports and indirect connection between origin and destination points (Wang and Wang 2011). Container transfer can only be finished at the hub port, that is, i-k-m-j is the container OD flow in the hub-and-spoke network, its design essence is to choose the best hub port among the alternative ports, and to determine the optimization deployment. From the view of liner firms, the design scheme is to achieve the lowest operating cost and shortest transportation time. Therefore, our model takes these two factors as the objective function and establishes a hub-and-spoke network to achieve scale economies and profit maximization..

3.2 Model construction

According to the discussions above, this paper explores the problems of fleet planning and shipping design under hub-and-spoke network. The purpose of this model is to minimize the weighted value of transportation cost and time by reasonable fleet allocation. We first define some basic symbols and definitions involved in modeling mathematically (see Table 1).

Before modeling, we illustrate the following assumptions: (i) The shipping network is relatively stable without considering uncertainties (i.e., wars, natural disasters); (ii) Each spoke port i, j only be allocated to one hub port k, and the two hub ports k, m are completely connected by trunk line k-m; (iii) Spoke port i, j cannot be directly connected, and all cargos need to transit through hub port k, m; (iv) The unit transportation cost C and the cost factors related to time ϑ are given in advance; (v) There is no limit of traffic capacity on the routes among the ports i, j, k, m; (vi) The vessel is considered as a whole without taking into accountthe cost associated with a single container; (vii) The transshipment situation is not considered, because the operation time and cost of transshipment are relatively small compared with the whole transportation process; (viii) Vessels v are carried out in the form of simple voyages; (ix) The number of each class vessel is a fixed value of in the shipping firm; (x) A total of V vessel types are determined.

The goal of this model is to minimize the weighted value of time and cost, that is $\lambda\vartheta Time + (1-\lambda)Cost,\ \lambda \in [0,1]$, ϑ is time-related cost factor. Specific objective functions are as follows.

$$\min \lambda\vartheta \sum_{i,j\neq i,k,k\neq m} t_{ij}(\mathrm{LD}_{ik} + \mathrm{LD}_{km} + \mathrm{LD}_{mj})\, X_{ijkm} \tag{1}$$

$$\sum_k Z_{ik} = 1 \forall i \tag{2}$$

$$Z_{ik} \le Z_{kk},\ \forall i,k \tag{3}$$

$$\sum_k Z_{kk} = p \tag{4}$$

$$\sum_m X_{ijkm} = Z_{ik},\ \forall i,k,j > i \tag{5}$$

$$\sum_k X_{ijkm} = Z_{jm},\ \forall i,m,j > i \tag{6}$$

$$Z_{ik},\ X_{ijkm} \in \{0,1\} \tag{7}$$

The objective function (1) represents the minimization of the total time-related cost; Constraint condition (2) ensures that each spoke port in the shipping network can only be assigned to one hub port; Constraint condition (3) means that tasks can be assigned to other ports only after port k has been determined as a hub port; Constraint condition (4) determines the number of hub ports as p; Constraint conditions (5) and (6) ensure that for any cargo flow (i, j) flowing through (k, m), ports i and j are assigned to hub ports k and m; Constraint condition (7) is determined and Z_{ik} 和 X_{ijkm} are a 0–1 variable. If the cargo flow between i and j passes through the hub nodes k and m, let $X_{ijkm} = 1$, otherwise, it is 0.

After completing the setting of hub-and-spoke network in the first stage, the position of hub points and port distribution are determined. Then the results obtained in the first stage are taken as the input of the second stage, this purpose is to study ship planning on our known network. The specific fleet planning model of the second stage is as follows.

$$\min (1-\lambda) \sum_{v,i,i\neq j,k\neq m} \left(C_{ik}^{v} N_{ik}^{v} + \alpha_v C_{km}^{v} N_{km}^{v} + C_{mj}^{v} N_{mj}^{v} \right) \tag{8}$$

$$\sum_{v} R_v N_{\mathrm{km}}^{v} \geq LD_{km},\ \forall k, m \tag{9}$$

$$\sum_{v} R_v N_{\mathrm{ik}}^{v} \geq LD_{ik},\ \forall i, k \tag{10}$$

$$\sum_{v} R_v N_{mj} \geq LD_{mj},\ \forall m, j \tag{11}$$

$$\sum_{v} V_{ik}^{v} \leq Z_{\mathrm{ik}},\ \forall i, k \tag{12}$$

$$\sum_{v} V_{mj}^{v} \leq Z_{mj},\ \forall m, j \tag{13}$$

$$\sum_{v} V_{km} = 1,\ \forall k, m \tag{14}$$

$$\sum_{v} N_{km} \geq \left(\sum_{k,m\neq k} Z_{kk} t_{km} \right) / f,\ \forall k, m \tag{15}$$

$$\sum_{v} N_{ik}^{v} \geq \left(\sum_{k,i\neq k} Z_{ik} t_{ik} \right) / f,\ \forall i, k \tag{16}$$

$$\sum_{v} N_{mj}^{v} \geq \left(\sum_{m,m\neq j} Z_{jm} t_{mj} \right) / f,\ \forall m, j \tag{17}$$

$$N_{ij}^{v} \in Z^{+},\ V_{km}^{v} \in \{0,1\},\ LD_{km} \in R^{+} \tag{18}$$

Table 1 Notations

Parameter	Symbol	Description
	Subscript i, j, k, m	Shipping ports in the hub-and-spoke network
	Superscript "+"	The set of positive real number
	λ	Weight, [0,1]
	f	Minimum frequency of service required on the route (Fixed at 7 days)
	ϑ	Time-related cost factors
	p	The number of hub ports
	$\forall$	for any of
Main variables	Z_{ik}	If port i is assigned to hub port k, it is equal to 1, otherwise it is 0
	Z_{ii}	If port i is the hub port, it is equal to 1, otherwise it is 0
	X_{ijkm}	Starting from port i, pass through hub ports k and m to reach the flow of destination port j;
	N_{km}^{v}	The number of vessel type $v \in V$ in ship route k-m
	V_{km}^{v}	If vessel type is $v \in V$ in the ship route k-m, it is 1, otherwise 0
	t_{ij}	Transportation time from port i to port j at predetermined speed
	C_{ik}^{v}	Shipping expenses of vessel $v \in V$ between port i and k at predetermined speed
	C_{km}^{v}	Shipping expenses of vessel $v \in V$ between port k and m at predetermined speed
	C_{mj}^{v}	Shipping expenses of vessel $v \in V$ between port m and j at predetermined speed
	R_v	Ship capacity $v \in V$
	LD_{ik}	The volume of freight transport of ship route i-k
	LD_{km}	The volume of freight transport of ship route k-m
	LD_{mj}	The volume of freight transport of ship route m-j
	α_v	Scale economy factors of vessel $v \in V$

Constraint condition (8) refers to the minimum transportation cost. Constraint conditions (9), (10) and (11) indicate that the total number of ships in each branch line and trunk line must carry the freight volume of this line. Constraints (12), (13) and (14) ensure that only one vessel type can be operated on each branch or trunk line. Constraint conditions (15), (16) and (17) require the number of vessels to meet the requirements of freight service. In the constraint conditions (18), we denote N_{ij}^{v} as integer variables, V_{km}^{v} as 0–1 variables, and LD_{km} as positive real numbers.

Based on the hub-and-spoke network model, this study analyzes the fleet planning of liner transportation. First, we expound the basic hub-and-spoke network structure. Single distribution and all cargo are transported from the initial spoke port to the destination, where the cargo must be transported through the hub port. This study elaborates the basic requirements of fleet planning, aiming to pursue scale economic benefit and to seek a balance between time and cost. Second, on the premise of ensuring the cargo volume of port demand, the befitting fleet allocation is realized by minimizing the weighted value of transportation cost and time. Third, in line with the two-stage heuristic algorithm of Zhang et al. (2015), we set up the hub-and-spoke network and fleet planning model respectively, and the problems are expressed in mathematical language to realize the concretized measurement.

4 Algorithm design

4.1 Rationale

The model established in this paper is a large-scale mixed integer linear programming model with complex structure, and the variables include both 0–1 type variables and discrete type variables, so it is difficult to solve the problem. The common solving method is to construct a heuristic algorithm, but the heuristic algorithm cannot always obtain the optimal solution. Instead, the optimal value of objective function is approached infinitely via continuous iterations, so as to obtain a satisfactory scheme (Segura et al. 2010). Therefore, the advantages and disadvantages of the heuristic solution need to be evaluated, assessing the difference between the numerical value and the theoretical value. Due to the difficulty of NP-hard problem itself, it is impossible to obtain the theoretical value directly in most cases, and then it is tough to judge the algorithm quality (Corus et al. 2019).

To solve this problem, the discrepancy between the numerical and theoretical values can be replaced by changing the difference between the upper and lower bounds of the numerical values. In this paper, Lagrange relaxation algorithm is applied, since the difficulty of solving can be greatly reduced by reducing certain constraints in the original problem.. When heuristic algorithms (i.e. genetic algorithm, simulated annealing method, tabu search method) are used, the searching time is long and the accuracy of optimal solution is not high (Youssef et al. 2001; Pothiya et al. 2008; Pham and Karaboga 2012; Mohammadi et al. 2016). However, Lagrange relaxation algorithm makes the model with reduced constraints and obtain the optimal solution within a certain time, in which the quality of optimal solution depends entirely on the parameters when absorbed into the objective function (Rafie-Majd et al. 2018). Next, the practical application shows that the lower bound obtained by the Lagrange relaxation method is of good quality and the calculation time is within the acceptable range. Meanwhile, using the basic notion of Lagrange relaxation, the heuristic algorithm can be built. The basic principle is to absorb the constraints that make the problem difficult to solve into the objective function through Lagrangian multipliers, while ensuring the linearity of the objective function of the original problem and the same solution to the previous and previous problems, so that the problem is easy to solve. The typical integer programming mathematical model is as follows.

$$z_1 = \min c^T x$$

$$s.t. Ax \geq b$$

$$x \in Z_+^n$$

where the decision variable x is n-dimensional column vector, c is n-dimensional column vector, A is $m \times n$ matrix, b is m-dimensional column vector; The coefficients A, b, and c are integers, and x is the set of non-negative integers member. For the above model, it is a relaxation of integer programming when an expression satisfies the following properties. The expression is:

$$Z_R = \min z_R(x)$$

The satisfactory conditions include: (1) the feasible solution region has compatible characteristics, $S \in \mathrm{S_R}$; (2) The objective function is compatible, $cx \geq z_R(x)$, $\forall x \in S$. Where S_R represents a solution set, and $\mathrm{Z}_R(x)$ is a real function.

4.2 Fundamental algorithm

Lagrangian relaxation algorithm is of large integer and mixed integer programming problem, by using a Lagrange multiplier vector to the introduce hard constraints into the objective function and format relaxation problems, which makes the research question into a relatively easier independent subproblems to solve. Further, we leverage Lagrange multiplier vector to coordinate for the minimization problem, leading the optimal solution of relaxation problem to become a lower bound of the original problem.

The Lagrange relaxation method consists of three parts: Lagrange relaxation, sub-gradient optimization algorithm, and feasible solution treatment. The main purpose of the first two items is to find the lower bound of the solution conforming to the constraint conditions, and the latter is to construct the heuristic algorithm based on Lagrange relaxation method. According to the basic principle of Lagrange relaxation problem, each corresponding λ Lagrange problem can be used as the lower bound value of original problem, and the optimal value of lower bound is z_{LD}. The solution method is completed by sub-gradient optimization algorithm, and then heuristic algorithm is applied according to the obtained value.

Therefore, the two basic steps of Lagrange relaxation algorithm are as follows: the first step is to determine a λ value and solve the optimal solution x of the corresponding relaxation model; the second step is to make x feasible when x is not a viable solution to the original problem. The main purpose of sub-gradient algorithm is to solve Lagrangian duality problem z_{LD}, and expect that the lower bound of the original problem can be as large as possible. Thus, it going to approach the direction according to the growth of $z_{LR}(\lambda)$.

The basic definition of sub-gradient are as follows. We set Q that is composed of feasible solutions of linear model, which include a finite number of integer points, and the poles are x^k $(k \in K)$, then $z_{LR}(\lambda^*) = \min\left\{c^T x^k + (\lambda^*)^T(b - Ax^k)\right\}$. Set $I = \left\{i | z_{LR}(\lambda) = c^T x^k + (\lambda^*)^T(b - Ax^k)\right\}$, for any $i \in$ I, $s^i = b - Ax^i$ is sub-gradient of $z_{LR}(\lambda)$ at λ^*.

1. The basic steps of the sub-gradient algorithm are as follows:

Step 1: Selecting a Lagrange multiplier λ as the initial value, let $t = 1$;

Step 2: For λ, we select a sub-gradient s^t. If $s^t = 0$, then λ is optimal solution and the calculation procedure can be stopped. Otherwise, let $\lambda^{t+1} = \max\left\{\lambda^t + \theta_t s^t, 0\right\}$, and $t = t + 1$, repeating step 2.

The step size θ is to find an appropriate lower bound as soon as possible or to make a solution feasible that has been obtained. The usual methods are as follows:

$$\theta_t = \frac{z_{UP}(t) - z_{LB}(t)}{\|s^t\|^2}\beta^t$$

In this condition, $0 \le \beta^t \le 2$, β_0 is taken as value 2 generally. When $z_{LR}(\lambda)$ goes up, β_t stays the same. If no change about $z_{LR}(\lambda)$ occurs within a certain number of iterations, it is necessary to reduce the value by half to continue iterating. $z_{UP}(t)$ is an upper bound of the original model, which can be determined by the target value of a feasible solution; $z_{UP}(t)$ is corrected gradually with the change of t; $z_{LB}(t)$ is a lower bound of $z_{LR}(\lambda)$, usually $z_{LB}(t) = z_{LR}(\lambda)$.

2. The iteration stop principle are as follows:

1. The number of iterations shall not exceed the limit value T, where the advantage is easy to control the calculation complexity and the disadvantage is that the solution quality may not be guaranteed;
2. Let $s^t = 0 \in \partial z_{LR}(\lambda^t)$. This is an ideal situation, and it is the optimal solution of Lagrangian duality. In the actual solution process, due to the problem complexity and calculation error, such result is usually difficult to appear, and is often used $\|s^t\| \le \varepsilon$ as a substitute;
3. We set $z_{LB}(t) = z_{UP}(t)$. In the situation that both are variable, it means that the optimal solution of the original problem has been obtained, and the optimal value is $z_{IP} = z_{LB}(t) = z_{UP}(t)$;
4. λ or the target value $z_{LR}(\lambda)$ does not change by more than one specific value within the set number of steps. In the meantime, the target value is regarded to be unchanged and the calculation can be stopped. In specific applications, one of the above stopping principles can be adopted, and it can also be used comprehensively.

4.3 Solution method

4.3.1 Lagrange decomposition method

For the hub-and-spoke network planning problem in the first stage, Lagrange heuristic algorithm is mainly adopted to solve. In this study, constraint conditions (2), (5) and (6) are introduced into the objective function with Lagrange multiplier α, β, γ respectively to form the relaxation problem.

$$z_R(\alpha, \beta, \gamma) = \min \sum_i \sum_k L_{ik} Z_{ik} + \sum_i \sum_{j>i} \sum_k \sum_m \overline{F_{ijkm}} X_{ijkm} - \sum_i \alpha$$

$s.t.$

$$Z_{ik} \le Z_{kk}, \ \forall i, k$$

$$\sum_k Z_{kk} = p$$

$$Z_{ik}, X_{ijkm} \in \{0, 1\}$$

In the formula,

$$L_{ik} = \alpha_i - \sum_{j>i} \beta_{kij} - \sum_{j<i} \gamma_{kji},\ \overline{F_{ijkm}} = \lambda \upsilon t_{ij} Q_{ij} + \beta_{kij} + \gamma_{kji}$$

The above model can be divided into two sub-problems for solving.

[Subproblem 1]:

$$\min \sum_i \sum_k L_{ik} Z_{ik}$$

$s.t.$

$$Z_{ik} \le Z_{kk},\ \forall i, k$$

$$\sum_k Z_{kk} = p$$

$$Z_{ik} \in \{0, 1\},\ \forall i, k$$

[Subproblem 2]:

$$\min \sum_i \sum_{j>i} \sum_k \sum_m \overline{F_{ijkm}} X_{ijkm} - \sum_i \alpha_i$$

$s.t.$

$$\sum_k \sum_m X_{ijkm} = 1,\ \forall i, j > i \tag{19}$$

$$X_{ijkm} \in \{0, 1\}$$

Constraint (19) improves the Lagrangian lower bound to some extent, which means that every container between OD pairs flows through the hub port. Subproblem 1 and subproblem 2 are obtained on the basis of Lagrange decomposition method, in which subproblem 2 can be solved by a simple knapsack question, whose solution is equivalent to finding the minimum $\overline{F_{ijkm}}$ value and setting X_{ijkm} as value 1.

4.3.2 Sub-gradient method

In subproblem 1, according to a set of given Lagrange multipliers α, β, γ, a Lagrange lower bound $z_{LR}(\alpha, \beta, \gamma)$ will be obtained by solving subproblem 1 and subproblem 2. The best lower bound should be as close as possible to the theoretical optimal solution, i.e.

$$z_{LR}(\alpha^*, \beta^*, \gamma^*) = \max z_{LR}(\alpha, \beta, \gamma)$$

Therefore, finding the optimal lower bound becomes to find the optimal Lagrange multiplier. In order to finish this step, this paper searches for the optimal combination of Lagrange multiplier in accordance with the sub-gradient way described above. The specific iterative steps are as follows.

Step1: If the optimal lower bound is not improved under the given number of iterative steps, it is necessary to adjust the search step of the sub-gradient method to half of the original step, and reset the Lagrange multiplier α, β, γ.

Step 2: Let formulas are iterated.

$$\text{For all } i,\ \alpha_i^+ = \alpha_i + t(\sum_k Z_{ik} - 1),$$

$$\text{for all } k,\ i,\ j > i,\ \beta_{kij}^+ = \beta_{kij} + t(\sum_m X_{ijkm} - Z_{ik}),$$

$$\text{for all } m,\ i,\ j > i, \gamma_{mij}^+ = \gamma_{mij} + t(\sum_m X_{ijkm} - Z_{jm})$$

where

$$t = \frac{Zb - Zl}{[\sum_i (\sum_k \overline{Z_{ik}} - 1)^2 + \sum_k \sum_i \sum_{j>i} (\sum_m \overline{X_{ijkm}} - \overline{Z_{ik}})^2 + \sum_k \sum_i \sum_{j>i} (\sum_m \overline{X_{ijkm}} - \overline{Z_{jm}})^2]} \Delta$$

In the above steps, Δ denotes the iteration step size, $\overline{Z_{ik}}$ and $\overline{X_{ijkm}}$ denotes the optimal values of two sub-problems respectively, Zl is the lower bound value of the objective function, and Zb denotes the optimal feasible solution of objective function. Therefore, the solution steps of subproblem 1 are as follows:

1. Let $Zb \leftarrow \infty$, $Zl \leftarrow 0$, and $\alpha = \beta = \gamma = 0$.
2. Finding an optimal value in subproblem 1, if the value is greater than Zl, then we assign it to Zl.
3. Substituting the obtained Z_{ik} value into the original function to get the upper bound Zb_1, if Zb_1 less than ∞, then we assign its value to Zb (i.e., the upper bound).
4. If one of the following conditions is satisfied, the optimal value will be reached and the calculation is stopped. Otherwise, going to Step 5.
   (a) $Zb - Zl \le$ the preset deviation value;
   (b) $\sum_k Z_{ik} - 1 = 0$, $\sum_m X_{ijkm} - Z_{ik} = 0$, $\sum_m X_{ijkm} - Z_{jm} = 0$;
   (c) If the iteration step size θ does not exceed a specific value within the set number of steps, the target value is considered to be unchanged;
   (d) The number of iterations exceeds the preset maximum iteration value.
5. Through the sub-gradient pattern, this paper updates the iteration step size Δ and θ, and go to Step 2.

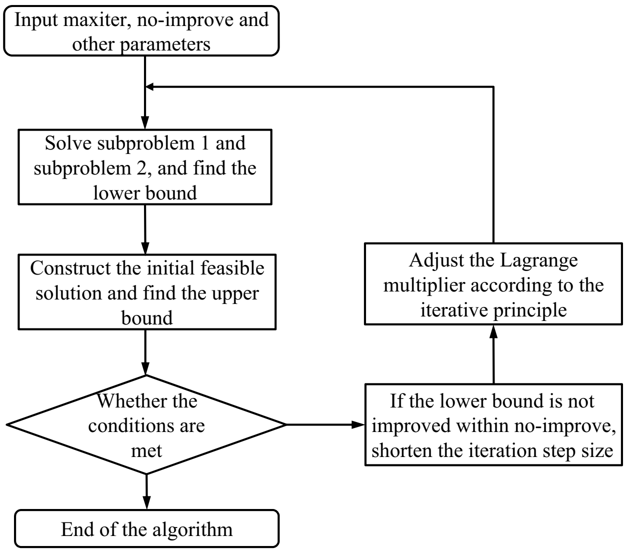

Fig. 2 Lagrange heuristic algorithm procedure

4.3.3 Lagrange heuristic algorithm

The above solving process achieves the first step of Lagrange decomposition algorithm and sub-gradient algorithm. Next, the heuristic algorithm is leveraged to construct the initial feasible solution for subproblem 1.

1. If $\sum_k \overline{Z_{ik}} > 1$, then for all k, we take $\overline{Z_{ik}} = 0$, search for $L_{in} = \min_k \{L_{ik} | Z_{kk} = 1\}$, to make $\overline{Z_{in}} = 1$.
2. If $\sum_k \overline{Z_{ik}} = 0$, then search for $L_{in} = \min_k \{L_{ik}\}$ to make $\overline{Z_{in}} = 1$·
3. For all $k, m, j > i$, leading to $\overline{X_{ijkm}} = \overline{Z_{ik}} \times \overline{Z_{jm}}$.

Based on the above procedures, the basic steps of Lagrange relaxation algorithm for hub-and-spoke network in the first stage are finished. The specific algorithm flow chart is shown as follows (see Fig. 2):

1. The variables are given the initial value by initialization. We set the search step as Δ, the count variable of search step as No-improve, the maximum iteration step value as maxiter, and the stop iteration standard as ε.
2. Solving subproblem 1 and subproblem 2, we get the optimal lower bound.
3. Constructing a feasible solution, the best solution *Zb* is gained in the iterative process.
4. Determining whether the solution meets the stopping condition, if so, we go to Step 7. If not, next step is moved on.
5. We update the Lagrange multiplier α, β, γ according to the iterative principle.
6. Stopping the calculation process, the optimal solution is output.

Once the shipping network is built, there is only a shortest path for every kind of cargo between OD, so the next step is to solve the second stage problem of ship planning. Based on the first stage of the hub-and-spoke network, we fix network design variables as parameters, i.e., $Z_{ik} = Z_{kk} = Z_{jm} = 1$, then solve and get the complete feasible solution in the subproblems.

$$\min (1-\lambda) \sum_{v,i,i\neq j,k\neq m} \alpha_v \left(C_{ik}^v N_{ik}^v + C_{km}^v N_{km}^v + C_{mj}^v N_{mj}^v \right) \tag{20}$$

$$\sum_v R_v N_{\mathrm{km}}^v \geq LD_{km}, \ \forall k, m \tag{21}$$

$$\sum_v R_v N_{\mathrm{ik}}^v \geq LD_{ik}, \ \forall i, k \tag{22}$$

$$\sum_v R_v N_{mj} \geq LD_{mj}, \ \forall m, j \tag{23}$$

$$\sum_v V_{ik}^v \leq Z_{\mathrm{ik}}, \ \forall i, k \tag{24}$$

$$\sum_v V_{mj}^v \leq Z_{mj}, \ \forall m, j \tag{25}$$

$$\sum_v V_{km} = 1, \ \forall k, m \tag{26}$$

$$\sum_v N_{km} \geq \left(\sum_{k,m\neq k} Z_{kk} t_{km} \right) / f, \ \forall k, m \tag{27}$$

$$\sum_v N_{ik}^v \geq \left(\sum_{k,i\neq k} Z_{ik} t_{ik} \right) / f, \ \forall i, k \tag{28}$$

$$\sum_v N_{mj}^v \geq \left(\sum_{m,m\neq j} Z_{jm} t_{mj} \right) / f, \ \forall m, j \tag{29}$$

$$N_{ij}^v \in Z^+, \ V_{km}^v \in \{0, 1\}, \ LD_{km} \in R^+ \tag{30}$$

This chapter mainly solves the modeling of hub-and-spoke network and fleet planning. First, the basic principle of Lagrange relaxation algorithm are introduced. Second, the hub-and-spoke network model is divided into two subproblems by Lagrange decomposition method, and the optimal solutions of the sub-problems are given respectively.

Table 2 Shipping times between different nodes in the network

	1	2	3	4	5	6	7	8	9	10
1	0	2.2	1.9	3.6	4.7	8.4	44.9	45	46	44.6
2		0	2.1	4.1	5.2	10.8	45.8	45.4	46.5	45.1
3			0	2.3	3.3	9	43.5	43.5	44.6	43.2
4				0	1.2	6.8	41.3	41.4	42.4	41.1
5					0	5.9	20.4	20.5	21.5	20.1
6						0	19.5	19.6	20.6	19.2
7							0	0.4	1.5	0.5
8								0	1.3	0.5
9									0	1.6
10										0

Third, based on the network structure of first stage, the relevant network design variables are fixed as parameters to solve the fleet planning problem, and the optimal solution of the whole problem is obtained.

5 Case study

5.1 Data selection

In order to verify the fleet planning model with regard to the hub-and-spoke network, the following necessary numerical analysis is carried out. This paper assumes that shipping firms employ large vessels that are known to be underutilized, with an average load rate of no more than 70%. In our case, the shipping freight of larger vessels is significantly lower than its capacity, for ensuring that the available quality of shipping services, shipping firms have to hire more ships. It is assumed that there exist 10 ports in the hub-and-spoke network, and the number of hub ports is (2, 3, 4). The positions of each port are generated randomly through the coordinate diagram, and the shipping time between ports can be obtained according to this coordinate diagram, as shown in Table 2. It is also assumed that the market container OD demand predicted by a shipping firm is shown in Table 3. The voyage cost between each node is shown in Table 4. According to the given hub-and-spoke network, the appropriate hub port nodes are selected to determine the basic network structure and route allocation, so that the total shipping cost and time can be minimized in the fleet planning.

To assign different weight values to transportation time and scheduling cost, this paper sets the λ value of (0.25,0.5,0.75), ϑ is set to value 4 on the basis of relevant information, the coefficient of scale economy is set to 0.6, and the minimum service frequency required on the route is set to 7. Ships carrying capacity is mainly divided into (2000, 4000, 6000, 8000, 12,000), the largest amount of each ship for (30, 25, 15, 15, 15), shipping route i-j time is: $t_{ij}=\frac{D_{ij}}{v_{ij}}$, the corresponding scale economy factor is approximately 0.6, and the current fleet consists of ship (0, 0, 10, 8, 6).

5.2 Simulation results

According to the Lagrange heuristic algorithm mentioned above, Matlab software is used to solve the procedure. The parameters are set as follows: Maxiter is set to 1000 times, ε is 0.01, and Δ is 2, and the results are shown in Table 5.

Table 3 Container flow between different nodes in the network

	1	2	3	4	5	6	7	8	9	10
1	0	76	65	47	62	200	22	120	88	72
2		0	130	60	141	351	58	60	166	42
3			0	33	56	137	32	39	67	42
4				0	73	191	16	31	72	19
5					0	351	35	50	104	35
6						0	273	214	513	158
7							0	116	56	71
8								0	65	343
9									0	44
10										0

Table 4 Shipping cost between different nodes in the network

	1	2	3	4	5	6	7	8	9	10
1	0	67	58	113	127	174	1354	1398	1430	1350
2		0	65	128	141	337	1410	1412	1444	1450
3			0	72	83	278	1352	1354	1386	1300
4				0	36	212	1285	1287	1319	1276
5					0	183	1157	1159	1191	1148
6						0	1073	1075	1107	1064
7							0	13	47	16
8								0	39	17
9									0	49
10										0

The Table 5 lists three groups of data corresponding to different number of hubs. The λ value is observed in the first column, the second column represents the selected hub port on the route, the next column represents the calculated time. Then the gap between Lagrange relaxation and the optimal solution is presented, and the last two columns are the number of vessel types at the hub port and the summary of all vessel types. For different p values, the ports that appear on the main routes are similar. The variation of λ will affect the calculation results, but the difference between the linear model constraint and the heuristic feasible solution is small. The last column gives the application of each ship type on each route. As mentioned above, the number of 12,000, 8,000, 6000 TEU ships operating on the ship route is 12, 10 and 10 respectively. While the shipping trend is to use large vessels to get the scale economy, our calculations suggest that the cheapest way is to operate small vessels. There exists cases where small ships replacing large ships can carry a high capacity. For example, for $p=3$, $\lambda=0.25$, five ships of class 4 ships and three ships of class 3 are replaced by eight ships of class 1. We randomly select two examples to compare the results of fleet planning with the original ship arrangement, as shown in Fig. 3 below.

According to the above bar chart, it is presented that under the same objective function, time and cost have the same effect, and the usage of small ships can save money and become more attractive, which is the best choice for firms to operate their shipping network.

Table 5 Calculate results

	Hub	Time(s)	gap	Hub Vessel (Vessel-No)	All Vess Type (Vessel No)
$p=2$					
λ = 0.25	5,7	43	5.01	4(1)	0(0), 1(3), 2(4), 3(5), 4(3)
λ = 0.5	5,7	42	4.39	4(1)	0(0), 1(1), 2(7), 3(4), 4(2)
λ = 0.75	5,7	42	3.89	3(1)	0(0), 1(3), 2(2), 3(6), 4(5)
$p=3$					
λ = 0.25	4,5,10	88	4.15	4(1)	0(0), 1(8), 2(0), 3(3), 4(3)
λ = 0.5	4,5,10	95	5.72	4(1)	0(0), 1(2), 2(5), 3(4), 4(4)
λ = 0.75	4,5,10	83	3.82	3(1)	0(0), 1(1), 2(2), 3(6), 4(6)
$p=4$					
λ = 0.25	3,4,5,10	152	4.12	4(1)	0(0), 1(0), 2(0), 3(4), 4(5)
λ = 0.5	3,4,5,10	144	3.17	3(1)	0(0), 1(6), 2(2), 3(4), 4(3)
λ = 0.75	3,4,5,10	149	5.85	3(1)	0(1), 1(0), 2(0), 3(6), 4(2)

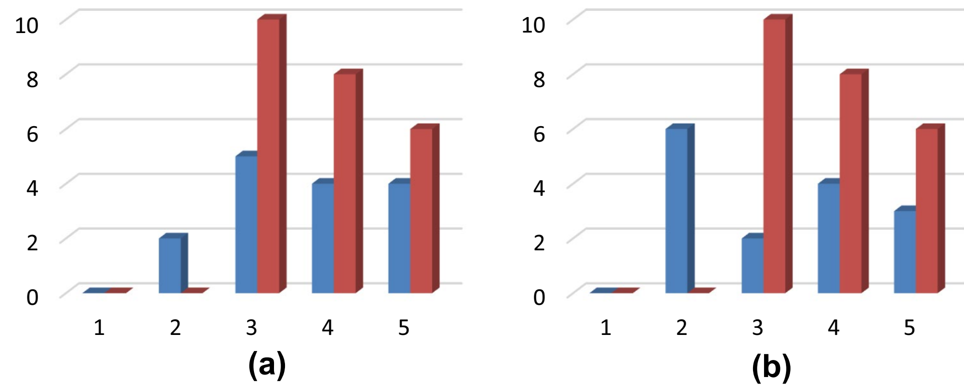

Fig. 3 Comparison between initial solution (red) and optimization solution (blue)

6 Conclusions

6.1 Theoretical and practical implications

Based on hub-and-spoke network, this paper mainly studies the fleet planning problem from the perspective of shipping firms. Network planning is an important issue, since the advanced network design is beneficial to reduce the operation time, save the transportation cost, and equip corresponding ships to adapt to different networks. This paper explores network design and fleet planning with mixed linear programming model, we fix network design variables as parameters to perform analysis and calculation. The main conclusions of this paper are as follows.

First, we establish the liner transportation fleet planning problem with regard to hub-and-spoke network. This integrated model in this study systematically reflect the operation situation of shipping firms, and provides concrete suggestions for shipping firms to allocate ships. Specifically, this paper puts forward an innovative method of two-stage model, that is, the first stage of hub-and-spoke network design and the second stage of fleet planning.

Second, the objective function of our hub-and-spoke network model is to minimize the weighted value of the operating cost and transportation time under the condition of satisfying the basic transport demand. Through a systematic literature review, it can be found that most studies only consider the transportation cost factors. But the conditional constraint of transportation time can reflect the service quality of shipping firms and the rationality of fleet planning, so it is an essential research factor.

Third, according to the fleet planning model of mixed integer programming in this paper, we apply Lagrange decomposition, sub-gradient and heuristic algorithm to construct the optimal solution. The Lagrangian decomposition method is used for obtaining the optimal value, and the heuristic algorithm is applied to build the feasible scheme. Compared with the general solution, this proposed mathematical model can obtain a high-quality solution in a short production time.

Finally, for the practical operations of shipping firms, having a certain number of small ships are able to improve the utilization rate and achieve scale economies. The average loading rate of shipping firms is usually not high, when firms blindly follow the trend of purchasing large ships, they probably will not recover funds in a short time to get scale merit. According to the analysis of our case study, it can be concluded that small ships have obvious cost advantages and are more conducive to the shipping firms to gain profits. However, in order to cope with the changes in market demand, it is still necessary to reservea few large ships.

6.2 Limitations and future research

In this paper, considering the hub-and-spoke network design and the liner fleet planning problems, we combine the Lagrange heuristic algorithm to verify the model effectiveness, but the actual problem often involves in many aspects, the paper simplifies some factors in the research process. Specifically, the following questions can be further study.

First, the hub-and-spoke network built in this paper is a regular standard form. Single distribution is selected between the hub port and hub port, and there is no capacity limit for the hub port. But the actual location of the hub port involves various considerations (i.e.geographical environment, regional economic status, local government policies). To be more consistent with the actual situation, integrating these factors in mathematical formula is a future research direction.

Second, future research could focus more on route allocation according to the network design of global liner, including demand and supply uncertainty, multi-periodicity, or more accurate heuristic algorithms. In essence, different decisions require distinct models, and the field of modelling and simulation is equipped with a range of approaches that can provide support to decisions at different levels of complexity (Currie et al. 2020). For instance, the COVID-19 pandemic is a special case of supply chain risks, which is distinctively characterized by a long-term disruption existence, disruption propagations, and high uncertainty (Ivanov 2020). The exploration of demand and supply uncertainties resulting from the pandemic should be a hot topic with great practical significance. Nowadays, supply chain network design should be viable enough to function well under complex business environments (Govindan et al. 2017).

Third, due to the great difficulty in obtaining various data of shipping firms in practice, this paper chooses the analysis method of numerical example, which may not fully reflect the actual mechanism. If conditions permit, the empirical survey should be carried out to make the research issues more suitable for practical operations.

Finally, for the liner shipping market, future research should not ignore that the competition among shipping firms and/or shipping alliances. Shipping firms tend to realize the scientificship planning to meet the standard of service quality, and minimize operating costs, so how to apply mathematical approach to improve the competitive relationship with shipping alliances is a theme worthy of in-depth discussion.

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