ISSN 1648-4142 / eISSN 1648-3480

2024
Volume 39
Issue 1
Pages 13–24

TRANSPORT

https://doi.org/10.3846/transport.2024.20531

Original Article

ROBUST OPTIMIZATION MODEL OF CONTAINER LINER ROUTES IN FEEDER LINE NETWORK

Xiaoling HUANG[1✉], Huanping CHEN[1], Jiaan ZHANG[1], Dan WANG[1], Jihong CHEN[2], Jack Xunjie LUO[3]

[1] *College of Transportation Engineering, Dalian Maritime University, Dalian, China*
[2] *College of Transportation, Shanghai Maritime University, Shanghai, China*
[3] *Tianjin Port Co. Ltd., Tianjin, China*

Highlights:
- take into account the enterprise's internal and external problems to be solved in parallel;
- the model foundation combines the planning and adjustment stages to study the optimization of container routes in the branch network;
- the uncertainty is introduced into the feeder robust optimization model and an internal feeder route optimization model based on robust strategy is established;
- in order to solve the robust optimization model, an improved taboo search algorithm is designed;
- robust solutions are not limited to finding the optimal solution in a specific scenario, but are applicable to each scenario.

Article History:
- submitted 7 July 2019;
- resubmitted 19 November 2019;
- accepted 3 February 2020.

Abstract. The universal application of the hub-and-spoke maritime network makes feeder line network key to restricting the quality and efficiency of maritime transportation. However, container liner routes in feeder line network are susceptible to the changes in shipment demand and international fuel prices. Therefore, based on the hub-and-spoke maritime network, this article constructs a robust optimization model of container liner routes in feeder line network. Under the capacity and time constraints, routes optimization and ship equipment under uncertain environment are analysed. An improved tabu search algorithm was designed based on the characteristics of the model. The example analysis proves that the model can still ensure the robustness of routes under uncertain environment, which is more applicable than the deterministic model.

Keywords: container liner routes, hub-and-spoke, feeder line, uncertain environment, robust optimization model, improved tabu search.

✉Corresponding author. E-mail: *huangxiaoling@dlmu.edu.cn*

Notations

C_k^f – unit fixed cost of ship k [¥/day];
C_s – transportation cost under scenario s [¥];
C_s^F – fixed cost under scenario s [¥];
C_s^H – cost of heavy fuel under the scenario s [¥];
C_s^{fuel} – fuel cost under scenario s [¥];
C_s^L – cost of light fuel under the scenario s [¥];
C_s^V – variable cost under scenario s [¥];
C_s^{port} – port related cost under scenario s [¥];
D^H – ship heavy fuel consumption rate [g/kW·h];
D^L – ship light fuel consumption rate [g/kW·h];
d_i^s – number of containers importing port i under scene s [TEU];
d_{ij} – distance from port i to port j [nmi];
f_i – standby time for arrival and departure at port i [h];
f_0 – standby times for arrival and departure at hub port [h];
G – port set, G = {0, 1, 2, ..., n}, $i, j \in G$, when i or j = 0, it means to call for the hub port;
l_i – path containing port i;
l_{ijk}^s – load of ship k from feeder port i to feeder port j under scenario s;
l_j – path containing port j;
l_{0ik}^s – load of the ship k from the hub port to the feeder port i under the scenario s;
l_{0k}^s – load of the ship k lea the hub port under scenario s;
M_k – admiralty coefficient of ship k;
n – number of feeder ports in the problem;
P_k – power of main engine of ship k [kW];
p_s – occurrence probability of scenario s;
Q_k – carrying capacity of ship k;
q_i^s – number of containers exporting port i under scene s [TEU];

r_s – price of heavy fuel under scenario s [¥/t];
r'_s – price of light fuel under scenario s [¥/t];
SM_k – mileage of ship k [nmi];
$STAP_k^s$ – stay time of ship k at ports under scenario s [h];
t_i – average loading and unloading speed of port i [TEU/h];
t_0 – average loading and unloading speed of hub port [TEU/h];
T_i – time of ship k reaching the hub port under scenario s [h];
T_j – meaningful only when X_{ijk} = 1, ensuring the continuity of navigation time of ship k under scenario s [h];
T_k – maximum sailing time of a single voyage of a ship [days];
T_0 – exit time of ship k departing from the hub port under scenario s [h];
u_k – port fee for ship k [¥];
V – ship set, $V = \{1, 2, ..., K\}$, $k \in V$;
v_k^s – speed of ship k under the scenario s [kn];
v_k^* – optimum speed with the lowest transportation cost [kn];
X_{ijk} – ship k shipping path;

$$X_{ijk} = \begin{cases} 1, \text{ when ship } k \\ \text{from port } i \text{ to port } j,\ i \neq j; \\ \\ 0, \text{ otherwise}, \end{cases}$$
$$\forall i, j \in G, \forall k \in V;$$

X_{i0k} – ship k finally returns to the hub port;
X_{0jk} – ship k starts from the hub port;
X_1 ... X_6 – optimal solution in scenarios 1...6;
Y_1 ... Y_3 – robust solutions corresponding to different decision preferences;
z_s – load slack under scenario s;
Δ_k – displacement of ship k [t];
Ω – scenario set, $\Omega = \{1, 2, ..., S\}$, $s \in \Omega$;
ω – weight coefficient.

1. Introduction

The trend of large ships and alliances is now obvious. For container transportation, the large ship not only means the reduction of unit transportation cost, but also means that the scale economies make the trunk and branch line container transportation develop and differentiate. This makes the application of the hub-and-spoke marine network more common (Zheng, Yang 2016; Tuljak-Suban 2018). The hub-and-spoke maritime network divides the ports into hub ports and feeder ports. Large container ships are mainly used for trunk transportation between hub ports, which form a trunk network. The small- and medium-sized ships are mainly used for branch line transportation between hub port and feeder ports, which form a feeder line network. The feeder line transportation network provides collection and distribution services for trunk container transportation. As the joint of trunk transportation, it affects whether the trunk transportation can proceed smoothly.

Container liner shipping can be considered as a network based industry. Its operation greatly depends on the design of shipping networks, formed by various routes (Tran, Haasis 2018). Liner shipping companies need to determine the service network structure that they undertake container cargoes in a certain time period. A regular and reliable feeder liner shipping network is important for shippers/consignees (Wang, Meng 2012). It relates to the comprehensive efficiency of liner shipping companies and determines the quality of marine transportation.

At present, the study of container liner routes in feeder line network is divided into 2 aspects: one is based on the deterministic environment, the other is based on the uncertain environment. Research in deterministic environment mainly includes liner route design (Du *et al.* 2017; Wang *et al.* 2014), liner fleet planning (Meng, Wang 2011), liner fleet deployment (Du *et al.* 2016; Yang 2015), and container ship speed optimization (Xing *et al.* 2019). However, there are few literatures on the study of feeder liner network in uncertain environment. The container liner routes are not as reliable as people expect, which is exposed to many uncertain risks, so it is very likely that transportation delay and total cost will change. Uncertainty of time, congestion at port, fluctuation of fuel prices, and uncertainty of shipment demand are all the reasons for the low reliability of container liner routes. Therefore, how to scientifically reflect the uncertainty in the optimization of feeder liner routes with quantitative methods, in order to reduce the decision-making risk and improve the operating income, has become the focus of liner companies.

2. Literature review

In order to improve the stability of route service and enhance its ability of resisting risks, the optimization of liner routes under uncertain environment has attracted more and more attention. Kepaptsoglou *et al.* (2015) uses chance constraints to solve the uncertainty of the ship's navigation time caused by weather conditions. Wang & Meng (2012) uses mixed integer nonlinear stochastic programming model to solve the uncertainty of waiting time and container handling time caused by port congestion. In the above research, multi-objective optimization is introduced to solve port time uncertainty (Song *et al.* 2015), but they mainly focus on the impact of time uncertainty on liner routes, and not considering the uncertainty of freight demand and fuel prices.

On the one hand, because of the influence of international trade market, hinterland economy and the diversion of alternative transportation mode, the stability of freight demand cannot be guaranteed, but the design of liner routes in feeder line network needs to be established based on the relationship between supply and demand. In order to describe demand uncertainty, interval sets (Liu, Yang 2016; Li *et al.* 2019), fuzzy set theory (Jung, Jeong

2012), stochastic programming (Zhang *et al*. 2019) are used as quantitative analysis tools of demand uncertainty. But these studies only guarantee the robustness of the model, not the robustness of the solution. Robust optimization method can guarantee the robustness of both solution and model (Li *et al*. 2017; Wang *et al*. 2012). Yang *et al*. (2017) established a robust optimization model to study the container feeder network with uncertain demand, which aims to minimize the costs of fuel, handling and penalty. But the seaworthy costs related to ships and port usage fees in route operation are not considered, while the waiting time and service time in port are ignored too. On the other hand, fuel costs could account for 50...60% of a ship's total operating cost in times of high fuel prices. The volatility of the bunker market over recent years has contributed to significant instability of cash flows for shipping lines (Wang, Teo 2013). At the same time, international fuel prices determine the optimal speed of a ship and affect the total sailing time of the route (Xing *et al*. 2018). Therefore, the current research generally adopts speed regulation to deal with the fluctuation of fuel prices (Yao *et al*. 2012; Magirou *et al*. 2015; Ronen 2011). However, when the market demand and fuel prices fluctuate at the same time, it will affect the choice of ship type for route adaptation, which is difficult to ensure the reasonable allocation of ship type for route (Xing *et al*. 2017). Therefore, only considering the demand uncertainty or fuel price uncertainty cannot guarantee the effectiveness of liner routes.

Therefore, this article studies the optimization of feeder liner routes with uncertain demand and fuel price. In order to ensure the robustness of the solution and the model, the robust optimization model of liner route in feeder line network is established. It aims to minimize the expected weekly operating cost and penalty cost of the route, and is constrained by the balance of line flow, capacity and time constraints. Compared with the existing uncertainty model, this article considers the fluctuation of both freight demand and fuel price at the same time. In order to optimize the ship type of route adaptation, the operating costs include not only the costs that vary with the cargo volume, fuel prices and port of call, but also the seaworthy costs associated with ships in the route network. At the same time, in order to reduce the impact of fuel prices fluctuation on the total operating cost, this article uses the partial derivative function of the total operating cost on the speed to determine the best speed. In addition, due to the different loading and unloading efficiency, busy degree and operation quantity of each port, the waiting time in each port of each ship in this article is different. Through the above processing, the applicability of the built robust optimization model for the liner routes in feeder line network is enhanced, and the robustness of the performance of the feeder line network is ensured when the freight demand and fuel prices fluctuate, so as to avoid the market risk.

3. Robust optimization model of liner routes

The hub-and-spoke shipping network refers to the feeder transportation network formed between coastal ports with the hub port, which is attached by the main line. Feeder line transport network includes regional hub ports, multiple feeder ports, feeder transport routes, etc. Fixed ships are engaged in foreign trade import and export container transportation between the feeder ports according to the published schedule or rules on the feeder routes. Taking the export container as an example, its function is to transport the containers to be exported from other feeder ports to the hub port through the feeder line, and then transfer them from the hub port to the destinations around the world through the main line. As the continuation of main transportation, container feeder transportation network undertakes the collection and distribution services of international logistics transportation in inland areas to a greater extent. Considering that the route is easily affected by the change of freight demand in the shipping market and the fluctuation of international fuel prices, the discrete scenario method is used to describe the uncertainty, and a robust optimization strategy is introduced to establish a robust optimization model for the design of feeder liner routes. Optimize the route network of feeder liner shipping companies in the uncertain environment. Therefore, from the characteristics of the hub-and-spoke shipping network, the form of container flow, and the way to describe uncertainty, the assumptions are making as follows:

- the hub port is determined and unique. Each feeder port is visited once. Each ship departs from the hub port and returns after passing through several feeder ports;
- the shipment demand (import and export) of feeder port is known, and the container flows between the hub port and the feeder port;
- the probability of occurrence of the scenario is known.

3.1. Objective function

The revenue of the liner company is equal to the difference between the operating income and the transportation cost. Operating income depends on the freight rate and shipment demand, which are largely determined by the market. Therefore, the cost level is the main factor determining the company's profit.

For any scenario s, transportation costs C_s consist of fixed costs C_s^F and variable costs C_s^V, as shown in Equation (1):

$$C_s = C_s^F + C_s^V. \tag{1}$$

Fixed costs C_s^F is the cost of keeping the ship's seaworthiness under the scenario s, such as depreciation, insurance, crew costs and maintenance costs. It has nothing to do with the volume of shipment transport, only related to the number of sailing days, the number of ships and the type of ship. Thus C_s^F is as shown in Equation (2); where

$STAP_k^s$ represents the stay time of ship k at ports under scenario s, as shown in Equation (3); SM_k represents the mileage of the ship k, as shown in Equation (4):

$$C_s^F = \sum_{k\in V} C_k^f \cdot \left(\frac{SM_k}{24 \cdot v_k^s} + STAP_k^s \right); \qquad (2)$$

where:

$$STAP_s = \sum_{\substack{i\in G \\ i\neq 0}} \sum_{\substack{j\in G \\ j\neq 0}} \frac{\left(\frac{\left(d_i^s + q_i^s\right)}{t_i} + f_i \right) \cdot X_{ijk}}{24} + \frac{\sum_{i\in G} \left(\frac{d_i^s}{t_0} + f_0 \right) \cdot X_{0ik}}{24} + \frac{\sum_{i\in G} \left(\frac{q_i^s}{t_0} + f_0 \right) \cdot X_{i0k}}{24}, \ \forall k \in V; \qquad (3)$$

$$SM_k = \sum_{i\in G} \sum_{j\in G} X_{ijk} \cdot d_{ij}, \ \forall k \in V. \qquad (4)$$

In Equation (3), $\sum_{\substack{i\in G \\ i\neq 0}} \sum_{\substack{j\in G \\ j\neq 0}} \frac{\left(\frac{\left(d_i^s + q_i^s\right)}{t_i} + f_i \right) \cdot X_{ijk}}{24}$ represents the dwell time of the ship k at the feeder port; $\frac{\sum_{i\in G} \left(\frac{d_i^s}{t_0} + f_0 \right) \cdot X_{0ik}}{24}$ represents the dwell time of ship k at the hub port, and then the ship k departs from the hub port to the feeder port; the ship eventually needs to return from the feeder port to the hub port, and $\frac{\sum_{i\in G} \left(\frac{q_i^s}{t_0} + f_0 \right) \cdot X_{i0k}}{24}$ represents the dwell time of the ship k at the hub port.

Variable costs C_s^V is the variable costs that changes with the volume of shipment transport, fuel prices and port of call. C_s^V includes fuel cost C_s^{fuel} and port-related cost C_s^{port} under scenario s, as shown in Equation (5):

$$C_s^V = C_s^{fuel} + C_s^{port}, \qquad (5)$$

where:

$$C_s^{fuel} = C_s^H + C_s^L; \qquad (6)$$

$$C_s^H = \sum_{k\in V} \frac{SM_k}{v_k^s} \cdot P_k \cdot D^H \cdot r_s; \qquad (7)$$

$$C_s^L = \sum_{k\in V} \frac{SM_k}{v_k^s} \cdot P_k \cdot D^L \cdot r_s'; \qquad (8)$$

$$P_k = \frac{\left(\Delta_k\right)^{\frac{2}{3}} \cdot \left(v_k^s\right)^3}{M_k}, \ \forall k \in V; \qquad (9)$$

$$C_s^{port} = \sum_{k\in V} \sum_{i\in G} \sum_{j\in G} u_k \cdot X_{ijk}. \qquad (10)$$

For any scenario s, C_s^{fuel} includes 2 parts, heavy fuel cost and light fuel cost, as shown in Equation (6). Equation (7)–(9) is derived from Shintani *et al.* (2007). Equation (7) represents the total heavy fuel cost under scenario s. For any ship k, the heavy fuel cost is $\frac{SM_k}{v_k^s} \cdot P_k \cdot D^H \cdot r_s$, where $\frac{SM_k}{v_k^s}$ represents the sailing time of ship k under scenario s. Similarly, Equation (8) represents the light fuel cost under scenario s. Equation (9) is a classic main engine power formula. In Equation (10), for any scenario s, C_s^{port} is related to the ship type used and the port of call. In summary, the total transportation cost under scenario s is shown in Equation (11):

$$C_s = \frac{1}{24} \cdot \sum_{k\in V} C_k^f \cdot \left(\frac{\sum_{i\in G} \sum_{j\in G} X_{ijk} \cdot d_{ij}}{v_k^s} + \sum_{\substack{i\in G \\ i\neq 0}} \sum_{\substack{j\in G \\ j\neq 0}} \left(\frac{d_i^s + q_i^s}{t_i} + f_i \right) \cdot X_{ijk} + \sum_{i\in G} \left(\frac{d_i^s}{t_0} + f_0 \right) \cdot X_{0ik} + \sum_{i\in G} \left(\frac{q_i^s}{t_0} + f_0 \right) \cdot X_{i0k} \right) + \sum_{k\in V} \left(\frac{\sum_{i\in G} \sum_{j\in G} X_{ijk} d_{ij}}{v_k^s} \cdot P_k \cdot \left(D^H \cdot r_s + D^L \cdot r_s' \right) \right) + \sum_{k\in V} \sum_{i\in G} \sum_{j\in G} u_k \cdot X_{ijk}. \qquad (11)$$

The robust optimization method is derived from the robust control theory. As a supplement to the stochastic optimization and sensitivity analysis, it is a new modelling method for studying uncertain optimization problems. It uses discrete scenario approach, Ω = {1, 2, ..., S}, to describe uncertainty, and $\sum_{s\in\Omega} p_s = 1$. The decision-making process seeks the best-performing robust solution, so the objective function of the robust optimization model of container liner routes in feeder line network is as shown in Equation (12) (Zhao *et al.* 2017):

$$\min \sum_{s\in\Omega} p_s \cdot C_s + \omega \cdot \sum_{s\in\Omega} p_s \cdot z_s, \qquad (12)$$

where: $\sum_{s\in\Omega} p_s \cdot C_s$ measures the robustness of the solution; $\omega \sum_{s\in\Omega} p_s \cdot z_s$ measures the penalty cost of destroying load constraints due to certain conditions; ω is the weight coefficient; since z_s in this article reflects the load relaxation under scenario s, ω reflects the value of unit shipment volume loss.

3.2. Optimal speed

For $\forall k \in V$, the transportation cost corresponding to the ship k under the scenario s is as shown in Equation (13); Equation (14) is the partial derivative of Equation (13); the optimum speed with the lowest transportation cost for $\forall k \in V$ is obtained by making $\frac{\partial C_s}{\partial v_k^s} = 0$, as shown in Equation (15):

$$C_s = C_k^f \cdot \left(\frac{SM_k}{24 \cdot v_k^s} + STAP_k^s \right) + SM_k \cdot \frac{\left(\Delta_k\right)^{\frac{2}{3}} \cdot \left(v_k^s\right)^2}{M_k} \times$$

$$\left(D^H \cdot r_s + D^L \cdot r_s'\right) + \sum_{i \in G} \sum_{j \in G} u_k \cdot X_{ijk}, \forall k \in V; \quad (13)$$

$$\frac{\partial C_s}{\partial v_k^s} = \frac{C_k^f \cdot SM_k}{-24 \cdot \left(v_k^s\right)^2} + \frac{2 \cdot SM_k \cdot \left(\Delta_k\right)^{\frac{2}{3}} \cdot v_k^s}{M_k} \times$$

$$\left(D_k^H \cdot r_s + D_k^L \cdot r_s'\right), \ \forall k \in V; \quad (14)$$

$$v_k^* = \left(\frac{C_k^f \cdot M_k}{48 \cdot \left(D^H \cdot r_s + D^L \cdot r_s'\right) \cdot \left(\Delta_k\right)^{\frac{2}{3}}} \right)^{\frac{1}{3}}. \quad (15)$$

It is known from Equation (15) that the optimal speed is independent of the decision variable X_{ijk}, but it is related to the ship's displacement, admiralty coefficient, fuel consumption rate, daily fixed cost and fuel prices. Thus, when the ship type and fuel prices are determined, the optimal speed is determined.

3.3. Constraints

Scenario changes under robust optimization can affect some constraints. Therefore, constraints are divided into design constraints and control constraints.

Design constraints are not subject to the uncertainty parameters. The design constraints in this article are mainly for the ship's route constraints:

$$\sum_{k \in V} \sum_{i \in G} X_{ijk} = 1, \ \forall j \in G, \ j \neq 0; \quad (16)$$

$$\sum_{k \in V} \sum_{j \in G} X_{ijk} = 1, \ \forall i \in G, \ i \neq 0; \quad (17)$$

$$\sum_{j \in G} X_{ijk} - \sum_{j \in G} X_{jik} = 0, \ \forall k \in V, \ i \in G; \quad (18)$$

$$\sum_{\substack{i \in G \\ i \neq 0}} X_{0ik} = 1, \ \forall k \in V; \quad (19)$$

$$\sum_{\substack{i \in G \\ i \neq 0}} X_{i0k} = 1, \ \forall k \in V. \quad (20)$$

Constraints (16) and (17) ensure that each feeder port has only one ship to visit. Constraint (18) is a route continuity constraint, which ensures that the ship must sail out after entering a feeder port. Constraint (19) ensure that each ship departs from the hub port. Constraint (20) ensure that each ship eventually return to the hub port.

Control constraints are affected by uncertainty parameters. Because this article considers the uncertainty of shipment demand and fuel prices. Fuel prices affect the speed, which in turn affect the route time. Therefore, the load and time constraints will be affected by the change of the scenario.

Constraints (21)–(25) are time limits, and Constraints (26)–(31) are load limits:

$$T_0 = \frac{\sum_{i \in G} \frac{d_i^s}{t_0} \cdot X_{0ik}}{24} + f_0, \ \forall k \in V; \quad (21)$$

$$\frac{SM_k}{24 \cdot v_k^s} + STAP_k^s \le T_k, \ \forall k \in V; \quad (22)$$

$$T_j \le T_i + \frac{X_{ijk} \cdot d_{ij}}{24 \cdot v_k^s} + \frac{\left(\frac{\left(d_i^s + q_i^s\right)}{t_i} + f_i \right) \cdot X_{ijk}}{24} - \left(1 - X_{ijk}\right) \cdot T_k,$$

$$\forall i, j \in G, \ k \in V; \quad (23)$$

$$T_j \ge T_i + \frac{X_{ijk} \cdot d_{ij}}{24 \cdot v_k^s} + \frac{\left(\frac{\left(d_i^s + q_i^s\right)}{t_i} + f \right) \cdot X_{ijk}}{24} + \left(1 - X_{ijk}\right) \cdot T_k,$$

$$\forall i, j \in G, \ k \in V; \quad (24)$$

$$\sum_{i \in G} \sum_{j \in G} d_i^s \cdot X_{ijk} = l_{0k}^s, \ \forall k \in V, \ s \in \Omega; \quad (25)$$

$$l_{0k}^s \le Q_k + z_s, \ \forall k \in V, \ s \in \Omega; \quad (26)$$

$$\sum_{i \in G} \sum_{j \in G} q_i^s \cdot X_{ijk} \le Q_k + z_s, \ \forall k \in V, \ s \in \Omega; \quad (27)$$

$$\left(l_{0k}^s - d_i^s + q_i^s\right) \cdot X_{0ik} = l_{0ik}^s, \ \forall i \in G, \ k \in V, \ s \in \Omega; \quad (28)$$

$$l_{0ik}^s \le Q_k + z_s, \ \forall i \in G, \ k \in V, \ s \in \Omega; \quad (29)$$

$$\left(l_{0ik}^s - d_j^s + q_j^s\right) \cdot X_{ijk} = l_{ijk}^s, \ \forall j \in G, \ k \in V, \ s \in \Omega; \quad (30)$$

$$l_{ijk} \le Q_k + z_s, \ \forall j \in G, \ k \in V, \ s \in \Omega. \quad (31)$$

Constraint (21) represents the departure time of ship k from the hub port under scenario s. Constraint (22) indicates that the total sailing time of ship k under scenario s does not exceed the maximum time limit. The Constraints (23)–(24) are meaningful only if $X_{ijk} = 1$, which ensures the continuity of the sailing time of the ship k under the scene s. Constraint (25) is the load at the time of departure of ship k under scenario s. Constraint (26) is the load limit for Constraint (25). Constraint (27) is the load limit of ship k returning to the hub port under scenario s. Constraint (28) is the load of the ship k from the hub port to the feeder port i under the scenario s. Constraint (29) is the load limit of Constraint (28). Constraint (30) is the load of ship k from feeder port i to feeder port j under scenario s. Constraint (31) is the load limit of Constraint (30).

4. Improved tabu search algorithm

Brouer *et al.* (2013) have proved that the liner route network planning is NP-hard problem. This article studies the robust optimization problem of container liner route in feeder line under the uncertain environment, which is the extension of liner route network planning problem and belongs to NP-hard problem at the same time, compared with the deterministic model, the robust optimization model increases the search space and difficulty to search the result. At present, modern heuristic algorithms such as genetic algorithm (Sun *et al.* 2017), simulated annealing algorithm (Kong 2015), particle swarm optimization algorithm (Fan *et al.* 2018) and ant colony algorithm (Xu *et al.* 2020) are widely used to solve robust optimization problem, but the algorithm is easy to fall into the local optimal solution. As a modern heuristic algorithm, tabu search has a good global optimization ability (Li, He 2015). The setting of tabu table makes the algorithm avoid falling into cycle iteration while searching for the optimal solution (Li *et al.* 2018), strengthen the ability and efficiency of searching, which is applicable to the model established in this article. However, the tabu search algorithm has strong dependence on the initial solution, and its quality of the initial solution determines the quality and efficiency of searching the optimal solution. At the same time, because tabu search is an extension of local neighbourhood search, its neighbourhood transformation criteria determine the distribution and quality of neighbourhood solution. The selection of neighbourhood transformation criteria not only affects the ability of mountain climbing but also the ability to jump out of local optimum. Therefore, this article improves the initial solution and neighbourhood transformation criteria. The improved tabu search algorithm is used to solve the model.

At the same time, the uncertainty is described by using discrete case methods in robust optimization. The decision-making process is to find the best-performing robust solution, that is, a solution, which is not optimal for some scenarios but relatively good for each scenario. When s is determined, the uncertainty problem is transformed into a deterministic problem. In order to verify the performance of the robust solution, this article divides the algorithm into 2 parts based on the improved tabu search algorithm. The 1st is to solve the deterministic problem and seek to determine the optimal solution under the scenario s. The 2nd is to solve the uncertainty problem and seek the optimal robust solution under uncertain scenarios.

4.1. Deterministic problem

The scenario s is determined, $p_s = 1$, and the probability of occurrence of other scenarios is 0. Thus the control constraint becomes a design constraint and $z_s = 0$. Uncertainty issues translate into deterministic issues. Therefore, the total transportation cost of the Equation (11) is used as an evaluation function.

Solution code. Give each port a unique number. The digital sequence represents a meaningful port sequence, which can distinguish the ports that are specifically visited by each route. For example, 0 represents the hub port and 1–10 represents 10 different feeder ports. The digital sequence 0–1–5–4–0–0–3–7–2–0–0–6–0–0–2–8–9–10–0 represents the solution X. It means that the feeder line network contains 4 routes:

- Route 1: 0–1–5–4–0. Ships from the hub port visit feeder ports 1–5–4 in turn and then return to the hub port;
- Route 2: 0–3–7–2–0. Ships from hub port visit feeder ports 3–7–2 in turn and then return to the hub port;
- Route 3: 0–6–0. Ships depart from hub port to visit feeder port 6 and then return to hub port;
- Route 4: 0–2–8–9–10–0. Ships from hub port visit feeder ports 2–8–9–10 in turn and then return to the hub port.

At the same time, the model constructed in this article contains a variety of ship types. Because the higher capacity of the ship under the scenario, the higher the cost involved. Therefore, each route uses the principle of minimum capacity under the premise of satisfying design constraints to allocate ship.

Initial solution. The construction methods of initial solution mainly include insertion method, nearest neighbourhood method, C–W saving method and scanning method. The insertion method, also known as the farthest insertion method, was proposed by Mole & Jameson (1976) to solve the vehicle routing problem. This method has the advantages of the nearest neighbourhood method and C–W saving method. When searching for the insertion position, the element is moved. It is often used to produce a high quality initial solution, improving the efficiency of the algorithm (Zhang *et al.* 2013). Therefore, this article uses the insertion method instead of the random method to produce Initial solution.

Neighbourhood transformation criteria. The most common neighbourhood transformation criteria are *k-opt*, *or-opt*, *2-swap*, λ-*interchange*. *k-opt* considers the arc in the route. *or-opt* considers the point on the route and improve the solution by switching the nodes inside the line. λ-*interchange*, node switching method, is composed of 1–0, 1–1 and 1–2. It improves the solution by switching the nodes between routes. In order to enhance the ability of the algorithm to climb and jump out of the local optimum, *or-opt* is used for transformation inside the route, and 1–0 and 1–1 are used for route-to-route transformation.

Tabu object and tabu length. For the above neighbourhood transformation method, a tabu list with the vector components of solution as tabu objects is established, as shown in Table 1.

Table 1. Tabu object

Transformation mode	Neighbourhood transformation criteria	Tabu object
Inside the route	or-opt	$(i, j, j + 1)$
route-to-route	1–0	(l_i, i, l_j)
	1–1	(l_i, i, l_j, j)

i, j represents port i and port j. Under the *or-opt* exchange method, port i and port j belong to the same path. Under the exchange method of 1–0 and 1–1, l_i represents the path containing port i, l_j represents the path containing port j, and $l_i \neq l_j$. For the above 3 kinds of tabu objects,

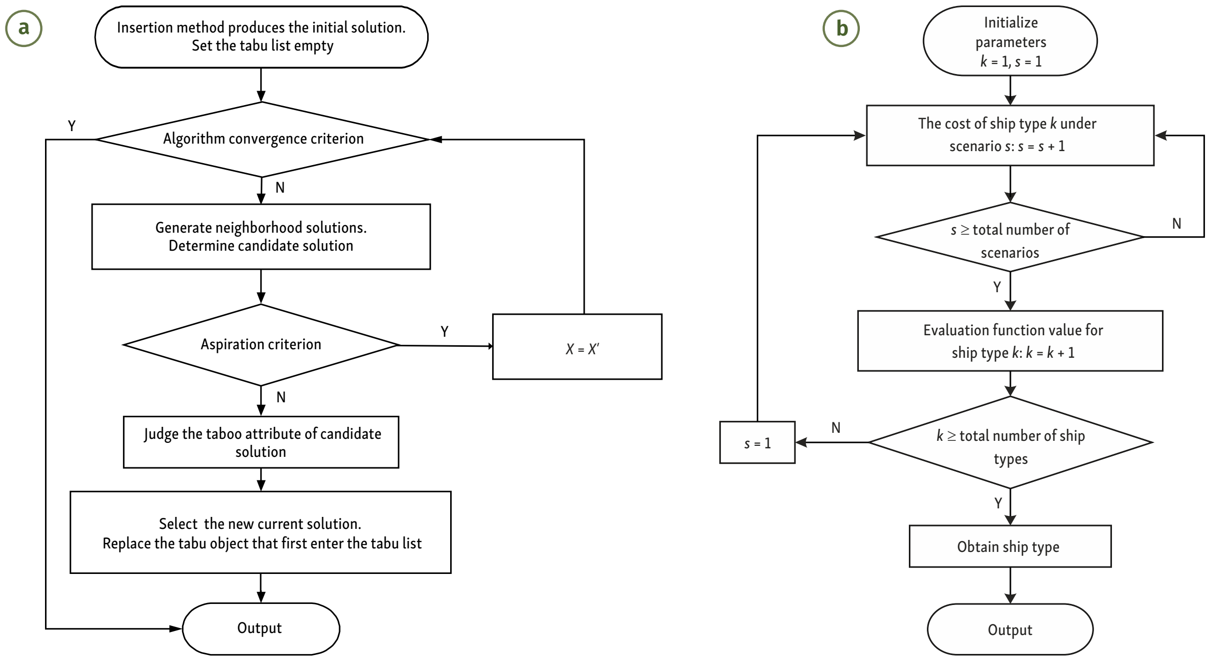

Figure 1. Flow charts: (a) – improved tabu search algorithm; (b) – selection of suitable ship type

the tabu length is set as $length = \sqrt{n}$, where n is the number of feeder ports in the problem.

According to the above improvement of the initial solution and domain transformation rules, as well as the setting of the tabu object and the tabu length, the improved tabu search algorithm in deterministic scenarios is shown in Figure 1a:

- Step 1: generate an initial solution X by using an insertion method, and set the tabu list empty;
- Step 2: judge whether the algorithm termination conditions are met. If they are, output the optimization results. if it is not, continue to Step 3;
- Step 3: using the constructed neighbourhood transformation criteria to produce neighbourhood solutions and determine candidate solutions from them;
- Step 4: dose the candidate solution meet the aspiration criterion? That is, when a solution X' better than the best solution X^{best}, has it appeared $\left(E\left(x'\right) < E\left(x^{best}\right)\right)$? If so, use the best X' to replace X to become the new current solution X^{best}, and replace the earliest tabu objects with the corresponding objects of X'. Then return to Step 2. If not, continue to Step 5;
- Step 5: the tabu attribute of each object corresponding to the candidate solution is judged. The best state corresponding to the non-tabu object in the candidate solution set is selected as the new current solution. At the same time, the tabu object that 1st enter the tabu list are replaced. Then return to Step 2.

4.2. Uncertain problem

Since the slack variable z_s is introduced under uncertainty, the load Constraints (26)–(31) are allowed to be broken. Therefore, the algorithm design under uncertain scenarios needs to change the evaluation function and the ship equipment principle based on the deterministic problem. For uncertain scenarios, $\sum_{s\in\Omega} p_s \cdot C_s\left(X_{ijk}\right) + \omega \cdot \sum_{s\in\Omega} p_s \cdot z_s$ as evaluation function and minimum transportation cost and penalty cost as ship equipment principle. Take any route l as an example, the ship's equipment process is as follows (Figure 1b):

- Step 1: initialize parameters, k = 1, s = 1;
- Step 2: calculate and record the transportation cost and penalty cost of the route l using ship k under the scenario s;
- Step 3: s = s + 1, is all scenarios traversed? Is to Step 4, no to Step 2;
- Step 4: calculate and record the evaluation function value of ship k, k = k + 1; are all ship types traversed? Is to Step 5, no s = 1, go to Step 2;
- Step 5: select the ship type with the smallest evaluation function value for route l.

5. Example analysis

The planning period is 6 months. Take the Bohai Sea area of China as an example. Dalian Port as the hub port, indicated by the number 0, and Jinzhou, Yingkou, Dandong, Qinhuangdao, Laizhou, Huanghua, Weihai, Yantai, Longkou, Weifang are feeder ports with sequence numbers 1...10. Shipping route operating time in weeks. Table 2

Table 2. Ship parameters

Q_k	C_k^f	Δ_k	M_k	u_k
260	15000	6579	215	5500
432	17500	10886	220	6000
633	22867	15192	240	7500
725	26300	18254	245	8500
991	32400	24503	257	10000

Table 3. Distance between ports

Port No	0	1	2	3	4	5	6	7	8	9	10
0	0	123	169	128	129	124	205	84	87	106	170
1	123	0	53	311	106	237	269	248	224	190	265
2	169	53	0	305	113	214	232	238	227	183	237
3	128	311	305	0	298	269	335	172	195	252	301
4	129	106	113	298	0	154	142	196	172	146	189
5	124	237	214	269	154	0	142	171	162	30	53
6	205	269	232	335	142	142	0	234	214	158	144
7	84	248	238	172	196	171	234	0	39	131	230
8	87	224	227	195	172	162	214	39	0	127	227
9	106	190	183	252	146	30	158	131	127	0	70
10	170	265	237	301	189	53	144	230	227	70	0

Table 4. Average loading and unloading speed t_i of port i

Port No	0	1	2	3	4	5	6	7	8	9	10
t_i	140	100	100	100	80	80	100	90	100	90	90

Table 5. Standby time f_i for arrival and departure at/from port i

Port No	0	1	2	3	4	5	6	7	8	9	10
f_i	2.5	2.6	2.5	2.5	2.4	2.4	2.6	2.7	2.5	2.6	2.6

Table 6. Shipment volume change

Shipment growth \ Port No		1	2	3	4	5	6	7	8	9	10
+5%	d_i	232	221	163	305	309	47	119	79	258	37
	q_i	281	114	298	85	196	171	204	108	50	118
0%	d_i	220	209	154	289	293	44	113	72	245	35
	q_i	266	108	268	90	186	162	193	102	47	112
–5%	d_i	209	198	146	274	278	41	107	68	232	33
	q_i	252	102	254	85	176	153	183	96	44	106

Note: d_i – inbound volume; d_i – outbound volume.

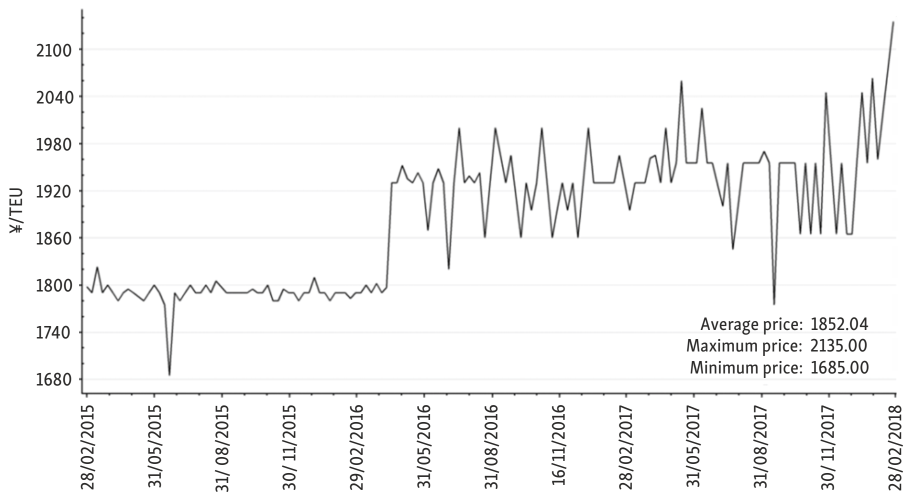

Figure 2. Container freight rates in the Bohai region (Bohai Sea Port Group, 2015–2018)

shows the ship parameters. Table 3 shows the distance between ports. Table 4 shows the average handling speed of port *i*. Table 5 shows the standby time at port *i*.

ω reflects the value of unit loss of transportation. This article reflects the penalty cost by measuring the value that can be generated by the lost shipment volume. This helps to reduce the error caused by subjective setting. According to the data provided by Wind (2018), the container freight rate in the Bohai region in 2015–2018 is analysed, as shown in Figure 2. Based on the average freight rate, ω = 1852.04 is set, and then the penalty cost $\omega \cdot \sum_{s \in \Omega} p_s \cdot z_s$ is calculated.

The fluctuation of freight demand in the shipping market is a normal state. Shipping enterprises can determine the total freight demand and change ranges by focusing on the market forecasts of all parties. In this article, they are shown in Table 6. In addition, according to the positive, conservative and negative attitude of the decision-makers towards the change of demand, the probability of the change of demand is changed. When the decision-maker holds a positive attitude, the probability of demand change of 5%, 0% and –5% is 0.5, 0.2 and 0.3 respectively; when the decision-maker holds a conservative attitude, the probability of demand change is 0.2, 0.5 and 0.3 respectively; when the decision-maker holds a negative attitude, the probability of demand change is 0.2, 0.3 and 0.5 respectively. The ship fuel market is affected by international crude oil price, weather, government policies, market intervention of Organization of the Petroleum Exporting Countries (OPEC) and International Energy Agency (IEA) (Xu 2011). The fuel prices will change with the market and will not be controlled by shipping enterprises. In this article, the fuel prices are divided into ordinary and expensive costs, as shown in Table 7. They are uniformly distributed in their respective intervals and their probability of occurrence is assumed to be 0.6 and 0.4, respectively. The heavy fuel and light fuel consumption rates (D^H, D^L) were 172g/Kw·h and 5g/Kw·h, respectively. As fuel prices and freight demand fluctuate at the same time, forming 6 possible scenarios, as shown in Table 8.

By using the improved tabu search algorithm and Matlab2014a software (*https://www.mathworks.com*), the optimal route scheme and corresponding ship type under different scenarios and decision preferences are obtained, as shown in Table 9. Take the rising market demand and high fuel price as an example, that is, in scenario 4, the optimal plan is to use 3 ships with 633 TEU capacity to visit the feeder port 9–5–10, 2–1, 7–3–8 from the hub port, and then return back; using one ship with 432 TEU capacity to visit the feeder port 4→6 from the hub port, and then return back. It can be seen from Table 9 that when

Table 7. Fuel cost

Price	r_s	r'_s
Ordinary	*U* [4256, 4700]	*U* [6300, 7100]
High	*U* [4700, 5100]	*U* [7100, 8150]

Note: *U* means the price division of tobacco oil with two different probabilities.

Table 8. Description of every scenario

Scenario	Shipment growth +5%	Shipment growth 0%	Shipment growth –5%
Ordinary	Scenario 1	Scenario 2	Scenario 3
High	Scenario 4	Scenario 5	Scenario 6

Table 9. Contrast of the optimal values for different scenarios

Scenario	Optimal solution. The best route plan and the corresponding ship [TEU]						
Scenario 1	X_1	route	0–4–1–0	0–5–0	0–9–10–6–0	0–3–0	0–2–8–7–0
		ship capacity [TEU]	633	432	432	432	432
Scenario 2	X_2	route	0–9–10–6–8–0	0–3–0	0–4–2–1–0	0–5–7–0	
		ship capacity [TEU]	432	432	724	432	
Scenario 3	X_3	route	0–8–7–0	0–4–2–1–0	0–9–5–10–6–0	0–3–0	
		ship capacity [TEU]	432	724	633	260	
Scenario 4	X_4	route	0–9–5–10–0	0–2–1–0	0–7–3–8–0	0–4–6–0	
		ship capacity [TEU]	633	633	633	432	
Scenario 5	X_5	route	0–4–6–10–0	0–3–7–8–0	0–9–5–0	0–2–1–0	
		ship capacity [TEU]	432	633	633	432	
Scenario 6	X_6	route	0–4–6–10–0	0–9–5–0	0–1–2–8–7–0	0–3–0	
		ship capacity [TEU]	432	633	633	260	
Robust solution under positive attitude	Y_1	route	0–5–8–0	0–3–0	0–9–10–6–0	0–4–7–0	0–2–1–0
		ship capacity [TEU]	432	432	432	432	432
Robust solution under conservative attitude	Y_2	route	0–4–6–8–0	0–3–0	0–5–10–9–7–0	0–2–1–0	
		ship capacity [TEU]	432	432	724	432	
Robust solution under negative attitude	Y_3	route	0–8–3–0	0–9–0	0–2–1–0	0–5–7–0	0–4–6–10–0
		ship capacity [TEU]	433	260	433	433	433

Table 10. Costs of each solution in different scenarios

Solution \ Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
X_1	589672	587067	582285	600166	595214	593602
X_2	642763	555400	550929	655651	567071	563321
X_3	700120	571754	527692	710036	582075	545470
X_4	589736	583813	580205	591149	588858	585016
X_5	627209	556137	546265	638920	560041	554254
X_6	747317	646730	538076	756562	657620	543063
Y_1	591122	559109	550702	602201	569783	561330
Y_2	599402	557122	550086	607038	565109	563542
Y_3	594113	563040	549026	604166	573324	561084

the freight demand and fuel price in the hub-and-spoke network of the container feeder line fluctuate, the ship configuration and the port visited in the route network will change. In this article, the decision-maker's preference is considered in the robust optimization model, and the robust solutions are different under various preference. In order to quantitatively analyse the specific differences between different optimization results in Table 9, this article analyses the actual costs (transportation cost and penalty cost) of different optimization results in different scenarios, and the results are shown in Table 10.

It is known from Table 10 that when the freight demand or fuel prices fluctuates, the optimization scheme based on the deterministic scenario has poor applicability. For example, X_6 is the optimal solution under Scenario 6, and the optimal value is 543063 ¥. But the cost in Scenario 1 is 747317 ¥, and the deviation is 204254 ¥. The cost of Y_1 is 591122 ¥ under Scenario 1, and the difference between the optimal solution under Scenario 1 is only 1450 ¥. Through the comparison and analysis, it can be seen that although the optimal route scheme obtained by the robust optimization model is conservative, the deviation between the optimal solution obtained under each scenario is kept in a relatively small range because it integrates all scenarios. It can ensure that the robust optimization schemes are better in any scenario. While different robust optimization schemes are obtained under different preferences of decision-makers. Y_1 has better performance in scenario 1 and scenario 4 due to its focus on rising freight demand. In the same way, Y_2 and Y_3 show the same trend. In addition, through the calculation and analysis of the average operating cost corresponding to each robust scheme, we can see that the average cost corresponding to Y_3 is relatively high, which is mainly due to the negative attitude focusing on the decline of freight demand. As a result, the route allocation is too conservative, resulting in a relatively high average volume of containers dumped. It also shows that negative decision preference is not suitable in the current freight market.

6. Conclusions

This article use the robust optimization method to optimize the route network of feeder line network, and the uncertainty of freight demand and fuel prices is introduced into the robust optimization model of feeder line by using scenario description method. It aims to minimize the total operating cost and penalty cost, meets the route, capacity and time constraints, introduces slack variables, and allows appropriate volume of container rejection. The seaworthy cost related to the ship is added to the operation cost to optimize the line fitting ship type.

This article uses the partial derivative function of the operating cost with respect to the speed to determine the optimal speed, so as to reduce the impact of fuel prices fluctuation on the operating cost. By setting up different stay time in each port, it reflects the different loading and unloading efficiency, busy degree and operation volume of each port. In order to solve the robust optimization model, an improved tabu search algorithm is designed.

Compared with the determined optimal solution in each scenario, the robust solution is not limited to seeking the optimal solution in a certain scenario, but suitable for each scenario. At the same time, different decision preferences make the robust optimization schemes different, but they have good stability in the face of freight demand and fuel prices fluctuations. Due to the difference of freight demand of each port affected by the hinterland economy, some feeder ports have large demand for freight, while some have little. If each feeder port is visited by different ships many times, it may improve the ship loading rate by splitting the demand of each feeder port.

Therefore, in the process of route optimization in the future, the situation that each feeder port is visited by different ships for many times will be considered.

Funding

This work was supported by the:

- Funding National Natural Science Foundation of China (Grant No 71371038, 71431001, 51409157);
- Funding Young Scholar Program of Humanities and Social Science of the Ministry of Education of China (Grant No 14YJC630008).

Disclosure statement

Authors do not have any competing financial, professional, or personal interests from other parties.

Author contributions

Xiaoling Huang and *Huanping Chen* conceived the study.

Xiaoling Huang and *Jihong Chen* designed the improved tabu search algorithm.

Jack Xunjie Luo collected the data.

Xiaoling Huang, *Jiaan Zhang* and *Huanping Chen* analysed data.

Huanping Chen and *Xiaoling Huang* constructed the robust optimization model and wrote the 1st draft of the article.

Jiaan Zhang and *Dan Wang* improved the structure of the article.

References

Brouer, B. D.; Dirksen, J.; Pisinger, D.; Plum, C. E. M.; Vaaben, B. 2013. The vessel schedule recovery problem (VSRP) – a MIP model for handling disruptions in liner shipping, *European Journal of Operational Research* 224(2): 362–374. https://doi.org/10.1016/j.ejor.2012.08.016

Du, J.; Zhao, X.; Ji, M. J. 2017. Inner branch container liner route network planning model considering cargo owners' preferences, *Journal of Transportation Engineering* 17(3): 131–140. https://doi.org/10.3969/j.issn.1671-1637.2017.03.014 (in Chinese).

Du, G.; Sun, C.; Weng, J. 2016. Liner shipping fleet deployment with sustainable collaborative transportation, *Sustainability* 8(2): 165. https://doi.org/10.3390/su8020165

Fan, H.; Li, C.; Jiang, X.; Xu, Z. 2018. The location of inland ports considering the reliability of the route under uncertain demand, *Journal of Management* 15(8): 1256–1264. https://doi.org/10.3969/j.issn.1672-884x.2018.08.019 (in Chinese).

Jung, H.; Jeong, S.-J. 2012. Managing demand uncertainty through fuzzy inference in supply chain planning, *International Journal of Production Research* 50(19): 5415–5429. https://doi.org/10.1080/00207543.2011.631606

Kepaptsoglou, K.; Fountas, G.; Karlaftis, M. G. 2015. Weather impact on containership routing in closed seas: a chance-constraint optimization approach, *Transportation Research Part C: Emerging Technologies* 55: 139–155. https://doi.org/10.1016/j.trc.2015.01.027

Kong, Y. 2015. *Research on Fuzzy Resource Constrained Project Scheduling Robust Optimization Based on Possibility Theory*. MSc Thesis. China University of Petroleum. Available from Internet: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201801&filename=1017809738.nh (in Chinese).

Li, J.-Y.; He, Z.-W. 2015. Optimization of reactive multi-mode project scheduling based on stochastic breakdown of resources, *Operations Research and Management Science* 24(6): 44–50. Available from Internet: http://www.jorms.net/EN/10.12005/orms.2015.0194 (in Chinese).

Li, S.; Liu, R.; Yang, L.; Gao, Z. 2019. Robust dynamic bus controls considering delay disturbances and passenger demand uncertainty, *Transportation Research Part B: Methodological* 123: 88–109. https://doi.org/10.1016/j.trb.2019.03.019

Li, X.; Zhong, Z.; Zhao, Q.; Yuan, R. 2017. Robust optimization for project portfolio selection problem with divisibility under information uncertainty, *Systems Engineering – Theory & Practice* 37(11): 2908–2917. https://doi.org/10.12011/1000-6788(2017)11-2908-10 (in Chinese).

Li, Y.; Fan, H.; Zhang, X.; Yang, X. 2018. Two-phase variable neighborhood tabu search for the capacitated vehicle routing problem with fuzzy demand, *Systems Engineering – Theory & Practice* 38(2): 522–531. https://doi.org/10.12011/1000-6788(2018)02-0522-10 (in Chinese).

Liu, H.; Yang, C. 2016. Robust research on service facility network design problem with demand uncertainty, *Operations Research and Management Science* 25(1): 117–125. Available from Internet: http://www.jorms.net/EN/10.12005/orms.2016.0016 (in Chinese).

Magirou, E. F.; Psaraftis, H. N.; Bouritas, T. 2015. The economic speed of an oceangoing vessel in a dynamic setting, *Transportation Research Part B: Methodological* 76: 48–67. https://doi.org/10.1016/j.trb.2015.03.001

Meng, Q.; Wang, T. 2011. A scenario-based dynamic programming model for multi-period liner ship fleet planning, *Transportation Research Part E: Logistics and Transportation Review* 47(4): 401–413. https://doi.org/10.1016/j.tre.2010.12.005

Mole, R. H.; Jameson, S. R. 1976. A sequential route-building algorithm employing a generalised savings criterion, *Journal of the Operational Research Society* 27(2): 503–511. https://doi.org/10.1057/jors.1976.95

Ronen, D. 2011. The effect of oil price on containership speed and fleet size, *Journal of the Operational Research Society* 62(1): 211–216. https://doi.org/10.1057/jors.2009.169

Shintani, K.; Imai, A.; Nishimura, E.; Papadimitriou, S. 2007. The container shipping network design problem with empty container repositioning, *Transportation Research Part E: Logistics and Transportation Review* 43(1): 39–59. https://doi.org/10.1016/j.tre.2005.05.003

Song, D.-P.; Li, D.; Drake, P. 2015. Multi-objective optimization for planning liner shipping service with uncertain port times, *Transportation Research Part E: Logistics and Transportation Review* 84: 1–22. https://doi.org/10.1016/j.tre.2015.10.001

Sun, H.-L.; Cui, Q.-Y.; Xue, Y.-F. 2017. Robust optimization for location-routing problem with uncertain demand under risk, *Operations Research and Management Science* 26(11): 26–34. Available from Internet: http://www.jorms.net/EN/10.12005/orms.2017.0256 (in Chinese).

Tran, N. K.; Haasis, H.-D. 2018. A research on operational patterns in container liner shipping, *Transport* 33(3): 619–632. https://doi.org/10.3846/transport.2018.1571

Tuljak-Suban, D. 2018. Competition or cooperation in a hub and spoke-shipping network: the case of the North Adriatic container terminals, *Transport* 33(2): 429–436. https://doi.org/10.3846/16484142.2016.1261368

Wang, S.; Alharbi, A.; Davy, P. 2014. Liner ship route schedule design with port time windows, *Transportation Research Part C: Emerging Technologies* 41: 1–17. https://doi.org/10.1016/j.trc.2014.01.012

Wang, S.; Meng, Q. 2012. Robust schedule design for liner shipping services, *Transportation Research Part E: Logistics and Transportation Review* 48(6): 1093–1106. https://doi.org/10.1016/j.tre.2012.04.007

Wang, T.; Meng, Q.; Wang, S. 2012. Robust optimization model for liner ship fleet planning with container transshipment and uncertain demand, *Transportation Research Record: Journal of the Transportation Research Board* 2273: 18–28. https://doi.org/10.3141/2273-03

Wang, X.; Teo, C.-C. 2013. Integrated hedging and network planning for container shipping's bunker fuel management, *Maritime Economics & Logistics* 15(2): 172–196. https://doi.org/10.1057/mel.2013.5

Wind. 2018. *Bohai Sea Port Group Freight Rate*. Wind Information Co. Ltd., Shanghai, China. Available from Internet: https://www.wind.com.cn

Xing, Y.; Yang, H.; Ma, X. 2018. Optimization of containership sailing speed and fleet deployment for continental ocean liner based on freight rate differentiation strategy, *Systems Engineering – Theory & Practice* 38(12): 3222–3234. https://doi.org/10.12011/1000-6788(2018)12-3222-13 (in Chinese).

Xing, Y.; Yang, H.; Ma, X.; Zhang, Y. 2019. Optimization of ship speed and fleet deployment under carbon emissions policies for container shipping, *Transport* 34(2): 260–274. https://doi.org/10.3846/transport.2019.9317

Xing, Y.; Yang, H.; Zhang, Y. 2017. Optimization model and algorithm of containership speed and fleet planning on ocean route basis, *Navigation of China* (2): 119–124. (in Chinese).

Xu, C.; Hu, J.; Huang, Y. 2020. Robust optimization of express delivery network with uncertain demand, *Computer Engineering and Applications* (3): 272–278. Available from Internet: http://kns.cnki.net/kcms/detail/11.2127.TP.20190327.1829.020.html (in Chinese).

Xu, W. 2011. *Research on Bunker Price Volatility and Hedging Strategy*. MSc Thesis. Dalian Maritime University, China. Available from Internet: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD2011&filename=1011111025.nh

Yang, H.; Zhao, X.; Liu, B.; Feng, Q. 2017. Robust optimization of container feeder logistics network under uncertain demand, *Logistics Technology* 36(2): 90–94. https://doi.org/10.3969/j.issn.1005-152X.2017.02.022 (in Chinese).

Yang, L.-Q. 2015. Scheduling model of feeder line multi-hull container ships based on hub-and-spoke network, *Chinese Journal of Management Science* (S1): 860–864. (in Chinese).

Yao, Z.; Ng, S. H.; Lee, L. H. 2012. A study on bunker fuel management for the shipping liner services, *Computers & Operations Research* 39(5): 1160–1172. https://doi.org/10.1016/j.cor.2011.07.012

Zhang, J.-H.; Li, J.; Gao, M.-G. 2013. Research on the open vehicle routing problem of with simultaneous deliveries and pickups, *Chinese Journal of Management Science* (4): 187–192. https://doi.org/10.16381/j.cnki.issn1003-207x.2013.04.010 (in Chinese).

Zhang, S.; Chen, M.; Zhang, W. 2019. A novel location-routing problem in electric vehicle transportation with stochastic demands, *Journal of Cleaner Production* 221: 567–581. https://doi.org/10.1016/j.jclepro.2019.02.167

Zhao, X.; Cao, B.-M.; Dou, J.-P. 2017. Robust optimal design of agri-food supply chain network under demand uncertainty and raw material price uncertainty, *Journal of Industrial Engineering and Engineering Management* (4): 178–185. https://doi.org/10.13587/j.cnki.jieem.2017.04.023 (in Chinese).

Zheng, J.; Yang, D. 2016. Hub-and-spoke network design for container shipping along the Yangtze river, *Journal of Transport Geography* 55: 51–57. https://doi.org/10.1016/j.jtrangeo.2016.07.001