Perishables Liner Bunkering Strategy and Route Optimization Considering Carbon Tax and Sulfur Emissions

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Abstract. For the issue of perishable goods liner shipping route selection and bunkering strategy, this paper gives full consideration to the characteristics of perishable goods, in the context of the carbon tax and the setting of emission control zones, constructs a mixed-integer nonlinear planning model with the goal of minimizing the total weekly cost of liner service, designs a segmented linear approximation algorithm for model solution, and conducts an arithmetic analysis based on the actual liner voyage as an example, which provides a reference for the actual operation of shipping.

1. Introduction

With the growing prominence of the shipping industry in global trade, container liner transportation plays a crucial role in cargo transportation. This paper focuses on optimizing the investment planning of shipping enterprises, particularly in the context of environmental challenges like carbon taxes and sulfur emissions. The study specifically delves into perishable goods container liner transportation, addressing complexities arising from their susceptibility to decay and carbon dioxide generation. The impact of international environmental regulations, such as carbon emission restrictions and sulfur emission control zones, further complicates the operational environment for vessels.

The research employs a mixed-integer nonlinear programming model to optimize route selection, refueling strategy, and sailing speed determination. The aim is to provide shipping enterprises with insights to enhance operational efficiency and promote sustainable development amid environmental pressures. The ultimate goal is to offer practical solutions for the green transformation of the global shipping industry, supporting enterprises in maintaining competitiveness in a dynamic environment.

2. Literature research

In liner transportation research, ship scheduling has been a key focus, categorized into strategic, tactical, and operational layers by Meng.[4] This study addresses tactical-level issues, focusing on refueling speed, route selection influenced by emission control zones, decisions on refueling ports, and modeling perishable goods transportation.


3. Problem description

This section provides a thorough description of the problem statement and assumptions.

On a given ocean container liner route, where the ports of call are known, the liner calls at each port in sequence from the starting port, loads and unloads cargo, and finally returns to the starting port. The shipping company determines the freight demand and tariffs on the route through the source survey, then the freight revenue is considered as a definite amount, and the total profit can be optimized by controlling the operation cost. The total operating cost of transporting perishable goods liner includes the fixed cost of the ship, fuel cost, port charges,

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perishable goods damage cost and other variable costs, and at the same time, combined with the carbon tax policy, the carbon emissions generated by the ship's voyage can be transformed into the carbon tax cost into it. Among them, fuel cost is one of the key factors affecting the operating efficiency of enterprises, especially with the implementation of the sulfur restriction order, the management of bunkering strategy is particularly important, and the formulation of a reasonable bunkering strategy, i.e., the reasonable selection of bunkering ports and the determination of bunkering volume are of great significance to reduce the total transportation cost. Meanwhile, the setting of sulfur emission control area, different ports can choose different routes between segments, different routes through the emission control area of different distances, in the emission control area can choose to use Marine Gas Oil (MGO) low-sulfur oil, in the emission control area can be used outside the low-sulfur oil (LSFO); ship port of call and the order of the ship is known, so it can be seen that the cost of the port for the determination of the amount, so need to be optimized for the other costs to ensure that the total profit is optimal. Assuming that the ports available for ship refueling can provide high quality low-sulfur oil LSFO and MGO, and ignoring the influence of weather and other environmental factors, the liner companies should, in principle, choose the refueling ports with low fuel price under the premise of ensuring safe fuel level; the sailing speed directly affects the fuel consumption, which in turn affects the timing of refueling and refueling volume decision-making; in the current downturn of the shipping market, the shipping companies can take measures to lower the speed of the ship to reduce the fuel cost and carbon tax, however, this will mean the cost of fuel and carbon tax will be reduced. Under the current shipping market downturn, shipping companies can reduce the speed of ships to reduce fuel costs and carbon tax, however, this will mean an increase in sailing time, i.e., an increase in the cost of refrigeration and spoilage in the transportation of perishables, and at the same time, it means that more ships need to be configured to satisfy the frequency of arrivals. To this end, the author aims to minimize the total operating cost of liner shipping including fixed cost, bunkering cost, refrigeration and spoilage cost of perishables and carbon tax in one round trip voyage, and studies the speed optimization and fuel replenishment problem considering carbon tax and perishables, as well as the route selection problem considering the setting of Emission Control Area (ECA), with the following basic assumptions:

- Only the fuel consumption of the ship's main engine is considered, and the fuel types are all low-sulfur oil LSFO and MGO;
- The ports of call are known and the cargo volume is stable and traceable;
- The same type of container ship is deployed on the route;
- Vessels are sailing at an even speed in each voyage section;
- The shipping interval on the route is one week and the ship's round-trip voyage time is determined.

4. Mathematical Model

The mathematical model developed in this paper is a mixed integer nonlinear programming model.

4.1. Model variables and parameters

The relevant variables are defined as follows: $Q'_k$ represents the mass of loss of perishable goods $k$; $T_k$ represents the transportation of perishable goods $k$; $B_{ij}$, take the value 1 if the ship sails along the segment $i$ route $j$, and 0 otherwise; $A_p$ take the value 1 if the ship refueled at port $p$ and 0 otherwise; $v^u_{ij}$ is the ship speed inside the ECA of route $j$ in sector $i$; $v^e_{ij}$ is the ship speed outside the ECA of route $j$ in sector $i$; $t^{i0}_j$ is the time of arrival; $Q$ is the Number of ships assigned; $q^p_L$ is ship refueling amounts of MGO at port $p$; $q^p_M$ is ship refueling amounts of LSFO at port $p$; $M^p_r$ is inventory of MGO while leaving at port $p$; $M^p_L$ is inventory of LSFO while arriving at port $p$;

The relevant parameters are defined as follows: $P = \{1, \cdots, p\}$ is the set of ports on the route; $K = \{1, \cdots, k\}$ is the set of perishable goods; $c^e$ is fixed costs of ships; $f$ is fixed bunkering costs for ships; $z^M$ is Port MGO Oil Prices; $z^L$ is Port LSFO Oil Prices; $c^e$ is the prices of perishable goods; $N_p$ is the amounts of perishable goods; $R$ is reefer unit time cost; $I_p$ is reefer amounts; $U$ is Host power; $v^e$ is Ship designed ship speed, kn. $d^v_{ij}$ is the distance of Segment $i$ route $j$ within the emission control area. $d^e_{ij}$ is the distance of Segment $i$ route $j$ outside the emission control area. $u^e$ is the carbon emission rate; $u^M$ is Carbon emission rate per unit of time for refrigerated containers; $e^v$ is the earliest time of arrival at the port; $l^e$ is the latest time of arrival at the port; $t^p_r$ is Port service time; $v^\text{max}$ is Maximum speed; $v^\text{min}$ is Minimum speed; $W^M_p$ is Ship's MGO Fuel Tank Capacity; $W^L_p$ is Ship's LSFO Fuel Tank Capacity; $h$ is maximum number of refuelings; $D^i_s$ is starting port for perishable goods $k$; $Q^i_s$ is arriving port for perishable goods $k$; $Q^c$ is Initial weight for perishable goods $k$; $\lambda_e$ is weight attenuation rate; $E$ is carbon tax rate.

4.2. Model formulation

The objective function is shown below:
The objective function represents the total operating cost minimization, which includes fixed cost, carbon emission cost, bunkering cost, perishable spoilage penalty cost, and reefer cold storage cost; Constraints (2)-(4) represent the time constraints, Constraints (5) represents the number of assigned ships versus time, Constraints (6)-(7) represent the speed limit; Constraints (8)-(11) represent the bunkering quantity constraints; Constraints (12)-(13) denote the oil volume incremental relation system; Constraints (14)-(17) denote the MGO and LSFO stock and storage volume constraints; Constraints (18)-(19) denote the refueling frequency constraints; Constraints (20) denotes the number of assigned ships constraints; and Constraints (21) denotes the 0-1 variable selection of the refueling ports and routes.

4.3. Model solution

In the model, there are both continuous decision variables and 0-1 type integer variables. The model involves both the reciprocal terms of decision variables and terms containing products and negative exponential functions of decision variables. Therefore, the model is categorized as a nonlinear mixed-integer nonlinear programming (MINLP) model. Directly solving this type of model can be challenging. To address this difficulty, the author employed linear transformation and piecewise linear approximation methods for the solution.

Given the characteristics of the model, the paper undertakes a linearization process to facilitate its solution.

-Reciprocal Method: \( V_{ij}^m = 1/\nu_{ij}^m, \quad V_{ij}^c = 1/\nu_{ij}^c \)

-Segmented linear approximation: linearization of the fuel consumption function and the perishable mass decay function. The function after segmented linear approximation is:

\[
Y^i(V_{ij}^m) = B_{ij} U(1/V_{ij}^c) v_i (d_{ij}^m / 24 V_{ij}^m) \quad (22)
\]

\[
Y^i(V_{ij}^c) = B_{ij} U(1/V_{ij}^c) v_i (d_{ij}^c / 24 V_{ij}^c) \quad (23)
\]

\[
Y^i(T_s) = Q_t^i / Q_c^i = (Q_t^i - Q_c^i) / Q_c^i = 1 - e^{-\lambda t_s} \quad (24)
\]

The above two classes of nonlinear functions can be solved using a certain number of linear segments to perform the approximation solution. The Gurobi Segmented Linear (PWL) constraint is a new generalized constraint that is a built-in function of gurobi to transform a nonlinear function into a linear function by means of a segmented linear approximation method.

5. Numerical experiments

The transatlantic route AEU 1, for example, passes through the ports of Tianjin-Shanghai-Xiamen-Singapore-Hamburg-Antwerp. The container liner route is shown in the Fig 1.

5.1. Model parameter

The ship is to undertake transportation of 20 kinds of perishable goods, and the ship is equipped with the same type of ship with the loading capacity of 10,000 TEU to be put into operation on this route. The minimum speed of the ship is 15 knots, the maximum speed is 25 knots, the fuel consumption coefficient of the ship is 0.012, the total operating cost of the ship in a single week is 150,000 US dollars, the capacity of the ship’s MGO tanks is 2,500, the capacity of the ship’s LSFO tanks is 2,500, the carbon
tax rate is 10, the maximum refueling number is 3, the ship's design speed is 18 knots, the maximum number of ships on the route is 15, and the refrigerated cost per unit time is 2. 60, maximum number of ships in the route is 15, cost of refrigeration per unit time is 2. The relevant parameters of ports of call are shown in Table 2. According to the relevant data, the segmented linear approximation of the decay function of 20 perishable goods is performed by the built-in function of Gurobi and solved by using the commercial software of Gurobi, so that the shipping company needs to deploy 6 ships on the route of AEU 1. The relevant parameters are shown in Table 1 and the results of the solution are shown in Table 2.

5.2. Model solving efficiency

Five sets of examples with uniformly increasing number of segments were constructed by varying the number of segments of the linear cut line, and the parameters with uniformly distributed values were taken as their median values for ease of calculation and comparison. For each set of cases, 10 calculations were taken to obtain the mean value to evaluate the effectiveness of the method. In this paper, Python Gurobi is used to simulate the fuel consumption function and mass decay function for the numerical solution of the model and cases. The number of segments is 20, the computation time is 0.59s, the number of segments is 40, the computation time is 0.83s, the number of segments is 60, the computation time is 1.56s, the number of segments is 80, the computation time is 2.48s, and the number of segments is 100, the computation time is 4.1s. The total cost tends to be optimal as the linear number of segments increases, but the computation time is constantly increasing, and the number of segments is increasing in order to seek the equilibrium of computation error and computation time. In order to find a balance between calculation error and calculation time, the number of segments is set to 80.

5.3. Sensitivity analysis

In order to test the effectiveness and applicability of the joint optimization strategy, this paper constructs a three-step optimization strategy and a two-step optimization strategy for control analysis, as well as analyzing the impact of the arrival time window and the carbon tax rate impact.

![Fig. 1. The AEU1 line route](image)

The three-step (solution1) optimization strategy optimizes the three strategies sequentially, while the two-step (solution2) optimization strategy optimizes the route and speed first, and then optimizes the refueling strategy, and the optimization scheme proposed in this paper is solution 3. Based on the three optimization strategies, as the LSFO fuel price changes, its total operating cost, refueling volume, speed, carbon emission and voyage time change as shown in Fig. 2, and the voyage time reflects the change of loss cost of perishable goods transportation. Fig 2-1 shows that Solution 2 having the highest total cost. There are two main reasons for the difference between the three approaches: the optimal route does not correctly reflect the effect of the change in ship speed during the route determination phase; and the assumptions in solution 1 and 2 motivate the ship to find a locally optimal route and speed solution between two ports.

<table>
<thead>
<tr>
<th>Port</th>
<th>Distance 1</th>
<th>Distance 2</th>
<th>Distance 3</th>
<th>PakingTime</th>
<th>ETA</th>
<th>ETD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tianjin</td>
<td>595.9</td>
<td>542.7</td>
<td>369.4</td>
<td>628.5</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Shanghai</td>
<td>376</td>
<td>387</td>
<td>221.9</td>
<td>434.3</td>
<td>186.8</td>
<td>532.4</td>
</tr>
<tr>
<td>Xiamen</td>
<td>789.7</td>
<td>1399.4</td>
<td>313.2</td>
<td>1560.5</td>
<td>168.7</td>
<td>1876.1</td>
</tr>
<tr>
<td>Singapore</td>
<td>2367.5</td>
<td>4614.5</td>
<td>2360.5</td>
<td>4914.5</td>
<td>2450.5</td>
<td>4198.4</td>
</tr>
<tr>
<td>Hamburger</td>
<td>241.1</td>
<td>257.4</td>
<td>127.8</td>
<td>387.5</td>
<td>154.3</td>
<td>229.9</td>
</tr>
<tr>
<td>Antwerpen</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2. Model solving results

<table>
<thead>
<tr>
<th>Port</th>
<th>Sections</th>
<th>Route</th>
<th>Fuel price(dollars/t)</th>
<th>speed/kn</th>
<th>Refueling amounts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>LSFO</td>
<td>MGO</td>
<td>ECA</td>
</tr>
<tr>
<td>Tianjin</td>
<td>1</td>
<td>1-2</td>
<td>392</td>
<td>827.5</td>
<td>17.21</td>
</tr>
<tr>
<td>Shanghai</td>
<td>2</td>
<td>2-1</td>
<td>460.5</td>
<td>769.5</td>
<td>17.73</td>
</tr>
<tr>
<td>Xiamen</td>
<td>3</td>
<td>3-1</td>
<td>371.5</td>
<td>843.5</td>
<td>19.24</td>
</tr>
<tr>
<td>Singapore</td>
<td>4</td>
<td>4-2</td>
<td>401</td>
<td>833</td>
<td>17.05</td>
</tr>
<tr>
<td>Hamburg</td>
<td>5</td>
<td>5-1</td>
<td>423.5</td>
<td>819.5</td>
<td>19.28</td>
</tr>
<tr>
<td>Antwerp</td>
<td>–</td>
<td>–</td>
<td>423.5</td>
<td>797</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 2. Sensitivity analysis comparison chart

Ensuring that other factors remain unchanged, the author analyses the refueling volume and speed in two scenarios with and without time windows. The results are shown in figure 2-2. Under the constraint of no time window, the sailing speed has more optimization space, and the ship can sail at a more uniform economic speed, thus effectively reducing the refueling cost and carbon emission; although the cost of perishable goods spoilage and refrigeration cost increases, the total operating cost decreases. Therefore, in order to improve the economic benefits of shipping, shipping enterprises should strengthen communication with ports, and may appropriately relax the arrival time of ships. Keeping other factors constant, the author analyses the effects of carbon tax rate changes on carbon emissions, total costs, sailing speed, and refueling volume, as shown in Fig 2-3 and 2-4. Refueling volume, carbon emissions, and sailing speed all show a decreasing trend as the carbon tax rate increases. This is due to the fact that the carbon tax increases dramatically as the carbon tax rate increases, resulting in an increase in total operating costs. Liner companies need to reduce carbon emissions from fuel consumption by lowering speeds, so refueling volume decreases, but the decreases are smaller. The reason for this is that there is a lower speed limit and a port time window, so when the carbon tax rate is increased to a certain level, the ship's speed remains almost unchanged. In addition, from 0 to 60 USD/t, the cost of refrigeration increases by 0.5%, and the cost of perishable goods spoilage increases by 0.16%. In summary, it can be seen that. Changes in port fuel prices affect the choice of bunkering ports, and shipping companies need to develop different bunkering strategies based on different fuel price trends to more effectively reduce ship bunkering costs; the size of the carbon tax rate affects the speed of the liner transporting perishable goods and fuel replenishment decisions. Therefore, liner companies should emphasize the use of low-carbon technologies to reduce carbon emissions.

6.Conclusions

In order to design the optimal routes, speeds, refueling ports and refueling volumes for container liners transporting perishable cargoes under the background of carbon tax and sulfur emission control zones, this paper constructs a mixed-integer fractional linear programming model to optimize the three variables at the same time based on the law of the perishable cargoes' quality degradation in time and solves it by using segmented linear approximation algorithms, and selects the European and American shipping routes as the case studies for
comparative tests and sensitivity analyses. The European and American routes are also selected as case studies for comparative testing and sensitivity analysis. The results show that the proposed integrated optimization method produces the optimal route, speed and refueling volume in terms of total cost. The results of the case analysis verify the practicality and effectiveness of the proposed comprehensive optimization method, and provide theoretical support for the operation strategy of perishable cargo liner shipping. In the actual operation of shipping enterprises, shipping demand tariffs and fuel prices are fluctuating, and future research can further carry out joint optimization research in the context of uncertain markets.

References


