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Research on the Hub and Spoke Container Shipping Network Model with Marine Carbon Tax

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Abstract

The hub-and-spoke container shipping network is widely used in container shipping industry due to its advantage of "economies of scale". The popularity of the concept of "green shipping" and the proposal of shipping carbon tax by EU emphasize the necessity of taking the cost of shipping carbon tax into consideration while designing the hub-and-spoke container shipping network. This paper introduces the hub-and-spoke container shipping network and the calculation process for EU shipping carbon tax, and then establishes a mathematical model on hub-and-spoke container shipping network considering shipping carbon tax, with the objective of the lowest overall cost for the network i.e. the total of shipping cost and carbon tax cost.

Keywords

Hub-and-spoke container shipping network; Shipping carbon tax; Network configuration and overall cost; Green shipping.

1. Introduction

The international container transportation industry is developing vigorously. With the accelerated pace of Large-scale container ship, container liner enterprises try to use the idea of "scale economy" , aimed at cutting down cost. Further the tendency of alliances, large-scale ships and other means is developing continuously.

Meanwhile, these liner enterprises continue to reduce the number of ports of call, and choose a large port with good water depth conditions, advanced port facilities and perfect logistics network as the transport hub port. Therefore, the importance of this hub and spoke container shipping network is increasingly prominent. The reason is that the biggest advantage of the hub and spoke shipping network is the "scale economy" -- in the whole network, ports are divided into hub port and spoke port. The spoke port usually has low loading rate and less types of transport goods, while the hub port has obvious advantages. The goods can be transported to the hub port through the branch line firstly, and then through the main lines to complete allocation, which obviously improves the transportation efficiency. And the transportation discount coefficient between the hub ports further effectively reduces the transportation cost. At present, a large number of liner companies in the market have begun to build and improve their own hub and spoke container shipping network, which has a new evaluation on the route layout and port selection.

On the other hand, as a transportation industry with high energy consumption, the total amount of CO2 consumed by fuel oil is huge. In 2019, the global fleet's fuel consumption is 265 million tons and carbon emissions are 819 million tons. Considering that shipping accounts for 85% of international trade and transportation, it is still a great challenge for the shipping industry to achieve the emission reduction target. According to the above background, on the basis of the general hub

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and spoke container shipping network, in view of the impact of marine carbon tax on the current shipping industry, it is necessary to introduce marine carbon tax into the whole network as a cost into the total cost of the whole shipping network.

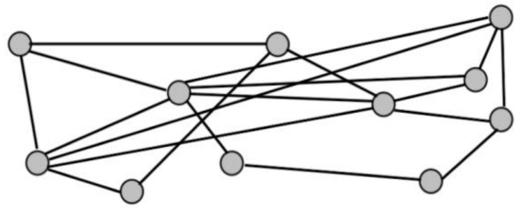
Many scholars have studied this problem. (Graça Costa M D,2008) explored the the problem of a single-configuration hub-and-spoke container network, then calculated the Min value of the time required for cargo volume processing at the hub port. (Sun Z, Zheng J,2016) proposed a two-stage model to study the optimization of hub port selection for non-existing hub ports, and demonstrated through the example of the Arctic Ocean route, that changing the status of non-existing hub ports will be It has a substantial impact on the entire hub-and-spoke shipping network. (Wu Qitao et al,2012) established an asymmetric proportion model, and studied the central position of hub and spoke container network hub with single configuration and unlimited capacity. The number of hub ports-total cost curve of network transportation presented a U-shape, and obtained the optimal hub port configuration result. (Zhang Zhao, 2017) introduced an attractive model in the optimization model of the hub-and-spoke shipping network, and used genetic algorithms to solve the hub port location problem.

Besides, (Chen Jie, 2017) used the energy consumption method to estimate China's maritime carbon emissions from the perspective of carbon emissions mainly from energy consumption, and studied the influencing factors of maritime carbon emissions from a national perspective. (Pierre Cariou and Ali Cheaitou, 2012) used two transatlantic liner routes as an example to compare the speed reduction of regional ships and the carbon taxation of CO2 emissions from ships. (Dai W L, Fu X, Yip T L, et al,2018), in view of the EU maritime carbon tax policy, believes that shipping costs will be affected by fuel prices, maritime carbon tax, loading and unloading costs, etc., which will affect the port selection results of the entire hub and spoke shipping network. (Chen jihong, Zhang hao, Luo ping,2016) analyzed the real purpose of the implementation of the European Union's carbon tax on navigation, and puts forward corresponding countermeasures and policy Suggestions on the basis of discussing the impact of this policy on China's maritime industry.

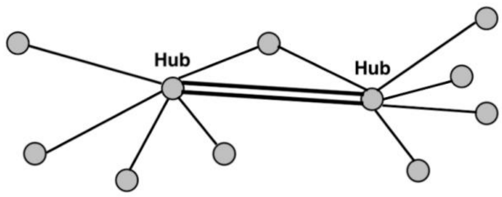
2. Analysis of the Hub and Spoke Container Shipping Network

2.1 Overview of the Hub and Spoke Container Shipping Network

With the prosperity of container shipping, the enlargement tendency of container ship is irresistible. Hub and spoke network is a kind of centralized transportation system around the super central hub. Its basic principle is that some nodes are regarded as the transmission hub. The logistics transportation starts from the starting point to the hub, then centralized transportation between the hubs, and finally to the final place. Such a simplified configuration optimizes the whole network structure. There will be transportation discounts between hubs that helpful to reduce the total transportation cost and effectively reduce the unit cost. The transportation between hubs improves the management efficiency, while the goods can be centralized to destinations. The utilization rate of node resources of the whole network has been improved. (See fig.1 shows the difference between the normal network and the hub and spoke network.）



(i) normal network



(ii) the hub and spoke network

2.2 Contents of marine carbon tax

The main content framework of EU maritime carbon tax is shown in Table 1:

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Table 1 Main Content Framework of EU carbon tax

SCOPE	All or part of maritime transport activities are applicable, whether or not their emissions occur within the EU region;
OBJECT	All ships of more than 5,000 gross tons entering, passing or leaving the ports of EU member states;
RATE LEVEL	Uncertain;
PAYMENT WAY	The ship can be at the port of call to pay on an annual basis.

The measurement of marine carbon tax is mainly to measure CO2 emissions and select carbon tax rate (marine carbon tax = CO2 emissions × marine carbon tax rate).

However, the measurement methods of CO2 emission can be divided into top-down method (i.e. based on fuel consumption, by multiplying the CO2 emission factor), bottom-up method (i.e. by pushing up the container cargo flow and unit carbon emission) [10]. At present, the most commonly used method is top-down method, so determining the carbon dioxide emission factor of fuel oil is the premise of calculating the whole marine carbon tax.

Carbon emission factor refers to the mass of carbon dioxide produced by burning unit mass energy. Generally, it can be obtained roughly by statistical data and accurately by experimental measurement. However, due to the differences of data collection method, experimental measurement process and result calculation procedure, the final values of different institutions are also different, so the average value is often used in practical application, and according to the results of IPCC, the value of carbon dioxide emission factor is fixed. In terms of marine carbon tax rate, what carbon tax collection index the European Union proposes to adopt for marine carbon tax has not yet been determined. However, according to Tran et al. [11], the optimal marine carbon tax rate is about 32 USD / CO2 ton.

2.3 The Impact of the Marine Carbon Tax on the Network

The general hub and spoke container shipping network does not consider any environmental cost, and it mainly aims at minimizing the total cost of the whole hub network to construct the network layout. However, when considering the environmental cost of marine carbon tax, we need to adjust the target, which is to minimize the total cost of transportation and marine carbon tax.

The cost of marine carbon tax is mainly determined by fuel consumption and marine carbon tax rate when the carbon dioxide emission factor of fuel can be determined. Therefore, the fuel consumption and carbon tax rate will affect the planning decisions of the relevant container liner companies on the layout of the shipping network. The decision-makers of shipping companies often adjust the network layout in order to reduce the cost of fuel consumption and navigation carbon tax as much as possible, which shows that the navigation carbon tax has a significant impact on the layout structure of the hub and spoke container shipping network.

Under the background of green shipping, whether the purpose of marine carbon tax is beyond reproach or not, we must pay attention to it. We should study the design of the hub and spoke container shipping network considering the cost of marine carbon tax as soon as possible, and change the goal of minimizing the total cost of transportation and marine carbon tax, which is quite appropriate The practical significance of.

3. Network Model

Based on the general hub-spoke shipping network, this paper establishes a hub-spoke container shipping network model considering marine carbon tax, and explores whether different marine carbon tax collection levels will affect the overall network layout.

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3.1 Model Establish

There are N ports in total, among which h are hub ports and (n-h) are spoke ports. It is assumed that the O-D quantity of heavy containers between each port is known. According to the principle of proximity, the spoke ports are allocated to each hub port. Finally, the model aims to minimize the total transportation cost of the whole shipping network (the sum of transportation cost and navigation carbon tax cost). In this paper, it is assumed that there is no limitation in traffic capacity among all ports while the hub ports are completely connected. And the spoke ports must transfer goods through one of the hub ports. On this foundation, marine carbon tax with continuously adjusted tax rate is included in the total cost of the whole network.

3.1.1 Basic assumptions

In view of the complexity of real container shipping, the following assumptions need to be made for model:

1.There is no capacity limit between all ports;

2.The location and quantity of ports are known in the shipping network;

3.Each spoke port can only connect one hub port;

4.Spoke ports under the same hub port can be connected;

5.Due to economies of scale, transport costs between hub ports will be lower than the costs of direct transport between spoke ports and hub ports. So there is a transportation discount coefficient is known which is set as 0.5;

6.In this shipping network, only one type of container ship is considered, and there is no distinction between heavy or empty containers, own containers or rental containers;

7. The structure of the shipping network is relatively stable;

8. The speed of container ships is known and fixed in all segments;

9. The cost of carbon tax is ignored during the period of being in port.

3.1.2 Parameters and decision variables

First of all, the parameters and decision variables that will be used in this mathematical model need to be explained. The main parameters are as follows

$N=(1,2,\ldots,n)$: The set of N ports in the hub and spoke container shipping network

Q_{ij} : The container flow between port i to port j (TEU)

D_{ij} : The distance between port i to port j ((nm)

C_{ij} : The unit transportation cost between port i to port j (USD/TEU)

α : The transport discount coefficient between hub ports (α =0.5)

v : The speed of the container ship (Kn)

K_h :the average consumption of heavy oil per TEU of container ship when sailing at speed v $(t/TEU\cdot h)$

K_l :the average consumption of light oil per TEU of container ship at speed v per unit time $(t/TEU\cdot h)$

r : The level of container carbon tax rate. $(USD/CO_2\text{吨})$：

$\lambda_l : CO_2$ emission factors of light oil $(CO_2\text{吨}/t)$

$\lambda_h : CO_2$ emission factors of heavy oil $(CO_2\text{吨}/t)$

$E : CO_2$ emission of container ship at speed v per unit time $(CO_2\text{吨}/TEU\cdot h)$; $E=K_h\lambda_h+K_l\lambda_l$

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The decision variables are described as follows：

$$X_{ij} = \begin{cases} 1, \text{A direct route between port i to port j} \\ 0, \text{Otherwise} \end{cases}$$

$$Y_{id} = \begin{cases} 1, \text{ Allocation of spoke port i to hub port d} \\ 0, \text{ Otherwise} \end{cases}$$

$$Y_{dd} = \begin{cases} 1, \text{ d is the hub port} \\ 0, \text{Otherwise} \end{cases}$$

$$Y_{ll} = \begin{cases} 1, \text{ ll is the hub port} \\ 0, \text{Otherwise} \end{cases}$$

3.1.3 Objective Function

The whole model aims to minimize the total network cost, which is mainly composed of the following parts: container transportation cost is the sum of all expenses of container liner companies for providing liner transportation services:

(1)Container transportation cost. According to the cost structure, it can be divided into: capital cost (including depreciation cost, interest, etc.), operation cost (including crew wage, ship supply cost, etc.), variable cost of voyage (mainly composed of fuel cost, port fees, etc.). This paper mainly studies the transportation cost of the hub and spoke container shipping network, so it will not refine the small cost.

① the transportation cost between all spoke ports at the same hub port:

$$\sum_i \sum_j Q_{ij} X_{ij} C_{ij}$$

②The transportation cost among all spoke ports to hub ports:

$$\sum_i \sum_j Q_{ij} (1 - X_{ij}) \left(\sum_d Y_{id} C_{id} + \sum_l Y_{jl} C_{jl} \right)$$

③The transportation cost between all hub ports:

$$\sum_i \sum_j Q_{ij} (1 - X_{ij}) \sum_d \sum_l Y_{dd} Y_{ll} a C_{dl}$$

the total transportation cost of the shipping network is W_t:

$$\sum_i \sum_j Q_{ij} \left[X_{ij} C_{ij} + (1 - X_{ij}) \left(\sum_d Y_{id} C_{id} + \sum_l Y_{jl} C_{jl} + \sum_d \sum_l Y_{dd} Y_{ll} a C_{dl} \right) \right]$$

(2) Cost of marine carbon tax.

Under the background of the European Union's marine carbon tax, CO2 emission from fuel combustion is included. And these caused an additional part in the final cost. So we consider the carbon emissions of heavy oil and light oil at the same time.

At present, the level of marine carbon tax collection is not clear in European Union. This paper plans to study the impact of marine carbon tax at different level T. According to the type of port's route, the cost of marine carbon tax can be divided into:

① the cost of marine carbon tax between all spoke ports under the same hub port:

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$$\sum_i \sum_j Q_{ij} X_{ij} TE \frac{D_{ij}}{v}$$

②Cost of marine carbon tax from all spoke ports to hub ports:

$$\sum_i \sum_j Q_{ij} (1 - X_{ij}) TE \left(\sum_d Y_{id} \frac{D_{id}}{v} + \sum_l Y_{jl} \frac{D_{jl}}{v} \right)$$

③Cost of marine carbon tax between all hubs:

$$\sum_i \sum_j Q_{ij} (1 - X_{ij}) TE \sum_d \sum_l Y_{dd} Y_{ll} \frac{D_{dl}}{v}$$

The total maritime carbon tax cost of the hub and spoke container shipping network:

$$\sum_i \sum_j Q_{ij} TE \left[X_{ij} \frac{D_{ij}}{v} + (1 - X_{ij}) \left(\sum_d Y_{id} \frac{D_{id}}{v} + \sum_l Y_{jl} \frac{D_{jl}}{v} + \sum_d \sum_l Y_{dd} Y_{ll} \frac{D_{dl}}{v} \right) \right]$$

To sum up, the objective function of this model is to minimize the total network cost：

$$MinW = W_t + W_c$$

$$= \sum_i \sum_j Q_{ij} \left[X_{ij} C_{ij} + (1 - X_{ij}) \left(\sum_d Y_{id} C_{id} + \sum_l Y_{jl} C_{jl} + \sum_d \sum_l Y_{dd} Y_{ll} a C_{dl} \right) \right]$$

$$+ \sum_i \sum_j Q_{ij} TE \left[X_{ij} \frac{D_{ij}}{v} + (1 - X_{ij}) \left(\sum_d Y_{id} \frac{D_{id}}{v} + \sum_l Y_{jl} \frac{D_{jl}}{v} + \sum_d \sum_l Y_{dd} Y_{ll} \frac{D_{dl}}{v} \right) \right]$$

3.1.4 Constraint Condition

According to the assumptions and model building requirements, the following constraints are set:

$$\sum_d Y_{dd} + \sum_l Y_{ll} = h \quad (1)$$

$$\sum_d Y_{id} = 1, \forall i \quad (2)$$

$$\sum_l Y_{jl} = 1, \forall j \quad (3)$$

$$Y_{id} \le Y_{dd}, \forall i, d \quad (4)$$

$$Y_{jl} \le Y_{ll}, \forall j, l \quad (5)$$

$$X_{ij} \le \sum_d Y_{id} Y_{jd}, \forall i, j \quad (6)$$

$$X_{ij} \in \{0,1\}, \forall i, j \in N \quad (7)$$

$$Y_{id}, Y_{jl} \in \{0,1\}, \forall i, j, d, l \quad (8)$$

Constraint 1 indicates that the number of hub ports is h; 2 and 3 indicate that all spoke ports can only be connected to one hub port;4 and 5 indicate that a spoke port can only connect to a hub port; 6 means that spoke ports under the same hub port can be connected, but spoke ports under different hub ports are not allowed to be connected, that is, there is no direct route; 7 and 8 are used as variable constraints.

3.2 Summary

This chapter establishes some assumptions, and creates the hub and spoke container shipping network model considering the cost of marine carbon tax, which takes the minimum total network cost as the

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objective function, while the total network cost includes the cost of container transportation and the cost of marine carbon tax.

4. Conclusion

Under the fierce competition of container shipping, the idea of "scale economy" is embodied in both large-scale ships and shipping alliance, which is also used in the hub and spoke container shipping network. The application of hub and spoke container shipping network is helpful to control the total transportation cost and improve the transportation efficiency of the whole network. Under the trend of "green shipping", how to implement low-carbon environmental protection in shipping industry has been concerned. The European Union's unilateral maritime carbon tax, no matter its fundamental purpose is good or bad, actually forces the container liner enterprises to take the cost of maritime carbon tax into account while planning their own hub and spoke shipping network, and take the lowest network cost as the goal. In reality, the hub-and-spoke container shipping network is a rather complex planning problem, and many aspects of it are simplified in this paper to facilitate model calculation, so there are still many shortcomings in this paper, which need to be further improved in the future research.

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