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OPTIMIZATION OF HUB-AND-SPOKE MARITIME NETWORK CONSIDERING HUB PORT FAILURE

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ABSTRACT

Any abnormal situation of the hub port may bring adverse effects such as time waste and cost increase to the shipping company. This paper solves the hub-and-spoke shipping network transportation optimization problem in the case of partial failure and complete failure of hub ports. Partial failure means that the transshipment demand of the hub port exceeds its capacity, resulting in congestion at the hub port. Complete failure means that the hub port cannot continue to provide services for some reason. The purpose of this paper is to optimize the hub-and-spoke shipping network system to minimize the cost loss of shipping companies in the event of hub port failure. This is a mixed-integer nonlinear programming problem. The simulation example proves that the model in this paper can effectively reduce the loss of cargo flow due to the failure of the hub port and significantly improve the reliability of the shipping network.

1 INTRODUCTION

Most of the world's cross-border trade in goods takes place by the sea. With the development of large-scale ships and the more accurate risk estimates of shipping companies, the volume of international trade completed by sea will continue to show an upward trend. By comparing the development of the shipping market vertically, it can be found that the shipping industry currently has the following development trends: Firstly, the large-scale development of container ships has formed economies of scale; Secondly, the economies of scale generated by the centralized transportation of goods on trunk lines are more obvious; Finally, the stability of the shipping network will increasingly depend on hub ports.

At present, hub-and-spoke shipping network is the most common shipping route model in the maritime transportation. It can concentrate the cargo volume on the regional routes to the shipping trunk line, form scale effect in trunk lines, improve the efficiency of cargo transportation, and thus reduce the unit transportation cost. In order to obtain a higher loading rate, the hub port will transfer many cargoes. When the hub port faces massive loading and unloading pressure and weak collecting and distributing system, there may be a risk of port congestion and stagnation not only, but there may also be some unexpected anomalies in the port. For example, when extreme weather such as tsunamis occur, it will cause the port to be forced to shut down. Disputes or workers' strikes within the port will make the daily work of the ports impossible to carry out smoothly. Damage to the system facilities of the port will affect the docking of ships. Although the probability of a hub port failure is small, a failure will cause incalculable damage. Our goal is to take the congestion cost function into account in the basic hub location model, simulate the freight process between actual ports, and determine the optimal transportation plan for container ships when the hub port is congested. This paper aims to solve the optimization problem of single-distribution hub-and-spoke shipping network after hub port congestion and propose effective suggestions for shipping companies.

It is the instinct of shipping enterprises to reduce the shipping costs and operation costs. It is of practical significance for shipping companies to choose hub-and-spoke network structure and route optimization schemes. The contributions of this study are as follows:

(1) Effectively optimize the overall planning scheme. By improving the hub-and-spoke network planning model, considering the capacity of the hub port, congestion, and failures, to achieve the goal of cost minimization.
(2) Optimize the overall spatial layout of the shipping network. Ports that are close to each other can develop different functions to avoid duplication of port functions and waste of resources.
(3) Realize the effective integration and distribution of port resources. Optimizing the route layout can effectively reduce the losses of shipping companies and related parties, and update strategies more quickly in continuous practice, making the route network more economical and stable.

The paper is arranged as follows. Section 1 describes the background and practical significance of the research. Section 2 reviews related research and summarizes the innovations of this paper. Then Section 3 introduces the proposed mixed Integer nonlinear programming model considering failure problems. Section 4 introduces the process of the simulation experiment and the results obtained by the simulation, determines the feasibility of the model, and analyzes the superiority of the simulation. Section 5 summarizes the full text and looks forward to future research.

2 LITERATURE REVIEW

Many scholars have conducted in-depth discussions on the location selection of land-based logistics distribution centers. Gan et al. (2015) solved the comprehensive multi-objective planning problem of minimizing the cost and maximizing the coverage of logistics services through simulation experiments and quantitatively optimized the relationship between facilities and the "specific environment" in which they are located. Gong et al. (2016) studied the routing problem of central granary location and route planning in China and used the immune calculation method to simulate the location and scheduling route of the central granary, which effectively improved the efficiency of grain circulation. Most of the articles on site selection simulation study onshore hub centers, but few people conduct site selection simulation research related to shipping. This paper will simulate the problem of how to optimize the entire shipping network when the hub port fails.

At this stage, many scholars' research on port failure is mainly to analyze the phenomenon of port congestion. Marinov et al. (2003) first combined the congestion problem with the construction of a hub-and-spoke network model and minimized the fixed and transportation costs of the queuing system network. Büt ün (2020) studied the problem of hub-and-spoke network design in the liner transport field and introduced the directional circulation center hub and freight routing problem, which considered the congestion and capacity limitation, establishing a mixed-integer linear programming (MILP) model to minimize the transportation cost. Waleed et al. (2020) tried to consider economies of scale and congestion costs in a multi-distribution hub-and-spoke network system. They established a cost-minimizing location model, using an improved Benders decomposition method to solve this problem. Yang Bin et al. (2016) believed that in hub-and-spoke networks, the attraction of economies of scale would lead to the possibility of congestion at hubs. They proposed a congestion cost function to balance economies of scale and network congestion costs. These studies reduce the loss caused by hub failure by improving the congestion problem, providing good optimization suggestions for the hub nodes in the case, and effectively improving the reliability of the transportation network.

In conclusion, few authors have studied the hub port failure problem and solved it by quantifying the congestion function and simulation experiments. Therefore, we construct a mixed-integer nonlinear programming model with a congestion cost function to fill the research gap in this field. Our goal is to minimize the total cost and verify the correctness of the positioning model through simulation. At the same time, the effectiveness of the simulation experiment in the site selection study is demonstrated.

3 METHODOLOGY

The hub-and-spoke network is widely used in the shipping network. The cargo from the feeder ports will be transported to the hub port in a centralized manner to generate economies of scale and save costs. The hub port undertakes the important task of concentrating and transferring cargo flow. Once the hub port fails, it will cause the surrounding transportation network congestion to increase or even collapse. This chapter will introduce the location model based on the hub-and-spoke shipping network and add the congestion cost function to the objective function of the model to make the model more realistic. We demonstrate the correctness and feasibility of the model by analyzing the impact of the model on the total cost of the system and changes in the shipping network.

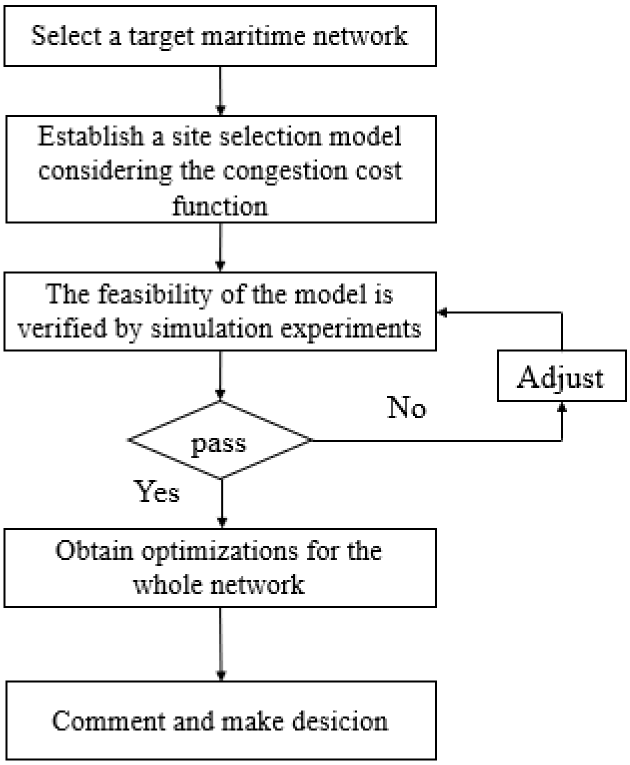

Figure 1：Produce in the research framework.

3.1 Problem Description

This paper focuses on the hub-and-spoke shipping network to study the problem of hub port failure. The use of a strict single-distribution hub-and-spoke network can simplify this complex problem. Figure 2. shows a typical single-distribution hub-and-spoke network. For exemple, the path with the red arrow is the shortest path from port F to port C.

According to the node uncertainty theory, this paper will analyze the partial failure and complete failure of the hub port. When a partial failure of a hub port occurs, shipping companies can choose to continue to wait or choose to detour to an alternate hub port. Due to the limited capacity of the port, there is a certain probability that the alternative hub port will be congested after the hub port completely fails and detours.

This paper will design a hub-and-spoke network with a strict single-distribution method. Among the network, branch ports are only allowed to connect with hub ports and are not allowed to sail with each other. Moreover, ships use a wrap-around route between hub ports, calling at ports in a certain order. Finally, limited capacity suggests that alternative hub ports will also face congestion, and that different failure scenarios at ports and various choices by shipping companies will affect the total cost of the entire hub-and-spoke network.

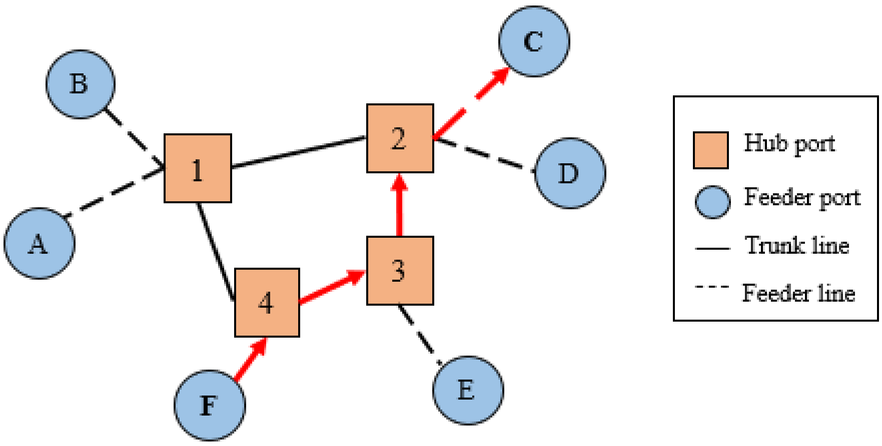

Figure 2： Schematic diagram of a hub-and-spoke network.

3.2 Hub-and-Spoke Network Location Model

According to the pivot location model of the classic P-hub median problem, combined with the characteristics of the hub-and-spoke network, the model of the hub-and-spoke network is established.

(1) Parameter description

Table 1: Description of the basic model parameters of the hub-and-spoke network.

Variable/Parameter	Instruction
P	Set of ports in the maritime network, $i, j, h, m \in P$.
i	Port of origin.
j	Port of destination.
h, m	The hub port h,m that the liner passes through.
k_0	Number of hub ports
f_h	The cargo volume of hub port h
λ	Discount factor between hub ports
c_{ij}	Transport cost per unit flows from port i to node j.
Z_{ij}	Total demand for containers between OD pair (i, j).
W_{ij}	$W_{ij} \in \{0,1\}$,1 if port i is assigned to the hub port j; 0 otherwise.
W_{ijhm}	$W_{ijhm} \in \{0,1\}$,1 if the vessel needs to pass through the hub port h and m transit during the transportation between OD pair (i, j); 0 otherwise.

(2) Model analysis

$$\min f = \sum_i \sum_j \sum_h \sum_m Z_{ij} W_{ihmj} (\tau(f_h) + c_{ih} + \lambda c_{hm} + c_{mj}) \tag{1}$$

$$\sum_h W_{ih} = 1, \forall i \in P \tag{2}$$

$$W_{ih} \le W_{hh} \tag{3}$$

$$\sum_h W_{hh} = k_0 \tag{4}$$

$$\sum_{m\in P} W_{ihmj} = W_{ih}, \forall i,\ j, h \in P \tag{5}$$

$$\sum_{h\in P} W_{ihmj} = W_{jm}, \forall i,\ j, m \in P \tag{6}$$

$$W_{ih} \in \{0,1\}, \forall i, h \tag{7}$$

$$W_{ihmj} \in \{0,1\}, \forall i, j, h, m \tag{8}$$

Equation (1) defines the total cost of cargo transportation in the maritime network as minimized, including (i) the congestion cost of the hub port, (ii) the transport cost from the feeder port i to the hub port h, (iii) the transport cost between the hub ports, and (iv) the transport cost from the hub port m to the feeder port j. Constraints (2) - (3) ensure that any node i or j in the network can only be uniquely assigned to a hub port. Constraint (4) defines the number of hub ports h in the network are k_0. Constraints (5) -(6) indicate that the port i is connected to the hub port j, and the port j is connected to the hub port m, then the cargo flow between OD pairs (i,j) can be transferred to the hub port h,m. Constraints (7) - (8) define the domain of the variables.

Referring to the method of quantifying the congestion function in Abbasi(2021), the flow-congestion cost function can be expressed by the following formula:

$$\tau(f_h) = a(\sum_h f_h)^b . \tag{9}$$

$\tau(f_h)$ is the cost of congestion， f_h indicates the volume of a hub port. The f_h can be regarded as a dimensionless value. Accordingly, a is taken as the dimensional coefficient, and the unit is the same as $\tau(f_h)$; $b \geq 1$.

To sum up, this paper will use the numerical simulation method to solve the proposed model, optimize the route in the case of port congestion by setting parameters in EXCEL software, and calculate the minimum total cost.

4 EXPERIMENTAL TESTS

We experimentally test the proposed model using real data provided by the Port and Shipping Logistics Laboratory of Dalian Maritime University. We briefly describe the required experimental data and analyze the experimental results.

4.1 Data and Parameter

We select 11 ports in some regions of the shipping network in Europe, the location map of each port obtained by using the drawing software is shown in the figure 3, assuming ports 1, 2, 3, and 4 are hub ports. Container delivery and pickup amounts follow a uniform distribution within [500,1000]. Loading and unloading costs and container freight rates between ports are all from the Port and Shipping Logistics Laboratory of Dalian Maritime University.

Parameters are set as follows: the hub port k_0 takes values of 3 and 4, respectively. The discount factors λ between hub ports are taken as 0.4 and 0.6 respectively to compare and discuss the results.

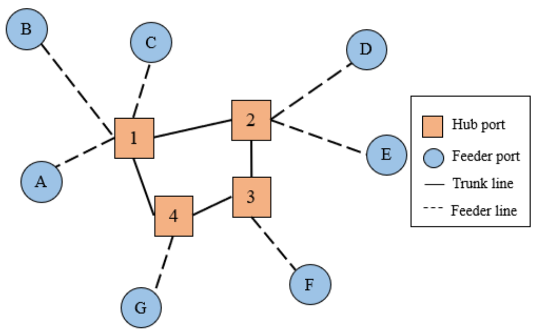

Figure 3：Schematic diagram of ports and routes.

4.2 Simulation Experiment Process

We first determined the total cargo flow between each port and based on the principle of the minimum total cost to obtain the shortest transportation path between ports. We will simulate the shipping process of shipping 10 batches of containers.

The calculation flow of the simulation example in this paper is as follows, figure 4 shows the flow chart of the simulation experiment:

Step 1: Maritime network initialization.

Step 2: The container ships in each port start to transport the first batch of goods to the destination port, solve the objective function value at this time, and draw the transportation network diagram at this time.

Step 3: Solve the optimal path of container ships for each transport. When the traffic volume exceeds the service capacity of the hub port, calculate the congestion cost at this time, and solve the alternate hub port and the optimal ship routing scheme.

Step 4: Analyze the changes in the transportation network when the values of k_0 and m are different, and the impact of changes in k_0 and λ on the hub port, and conclude.

Step 5: Output the optimal solution.

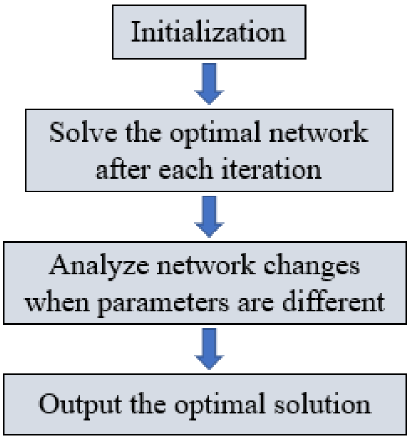

Figure 4: Flowchart of the simulation experiment.

4.3 Simulation Results

We simulated the failure of 4 hub ports respectively. After the hub port partially failed, due to the reduction of loading and unloading capacity, the regular flow of goods will be congested at the failed port, resulting in congestion costs. After calculation, let $\lambda = 0.4$, $k_0 = 3$, the cost of partial failure and complete failure is as follows:

Table 2: System cost of model.

Costing Items ($10,000)	Cost
regular shipping cost	225.90
Failure flow detour and congestion cost in case of partial failure	52.14
Failure flow detour and penalty cost in case of complete failure	538.20
the total expected cost of the system	816.24

As shown in the figure 5, when hub port 4 fails, the transportation network has changed. Containers in port 4 need to be transported to other ports through hub port 3. The feeder port G was originally connected to hub port 4, but at this time, it has become a hub port 3 to transport goods to other ports. And port 1 has become a direct transshipment of goods with port 3. As shown in the figure 6, when hub port 3 fails, the transportation network has changed. Containers in port F need to be transported to other ports through hub port 4, and goods in port 3 need to be transported to other ports through hub port 2, which is directly connected to hub port 4.

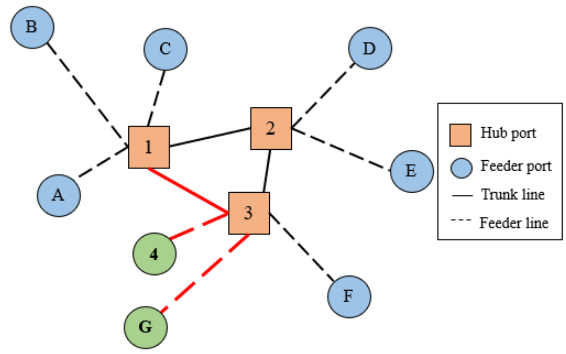

Figure 5:（$\lambda = 0.4$， $k_0 = 3$）Schematic diagram of hub port selection and branch port configuration.

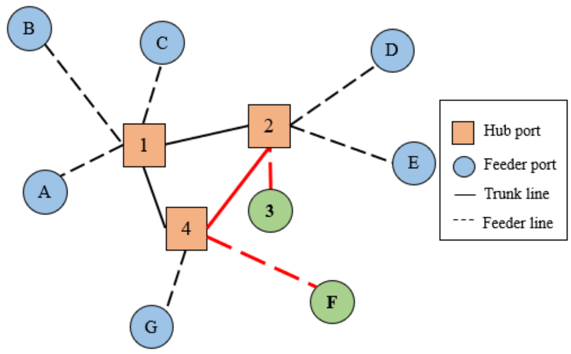

Figure 6:（$\lambda = 0.4$， $k_0 = 3$）Schematic diagram of hub port selection and branch port configuration.

As shown in Figure 7, when hub port 1 has a partial failure, the transportation network has changed（$\lambda = 0.4$， $k_0 = 4$）. As shown in Figure 3, when hub port 1 has a partial failure, the transportation network has changed. Due to the congestion at hub port 1, feeder port C went to hub port 2, feeder port A went to hub port 4, and the ships of port B chose to wait in place.

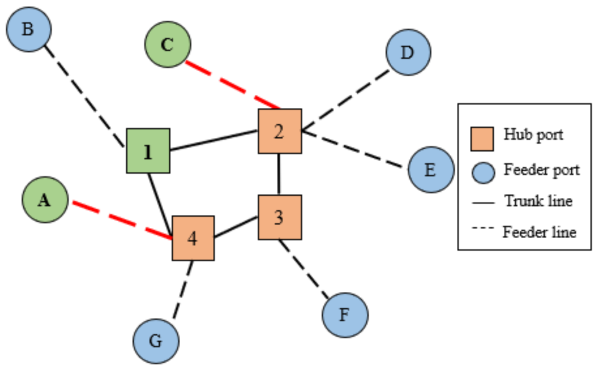

Figure 7:（$\lambda = 0.4$， $k_0 = 4$）Schematic diagram of hub port selection and branch port configuration.

When λ and k_0 take different values, the corresponding calculation results are shown in Table 3. Columns 4 to 7 represent the proportion of the cargo flow of each hub port to the total cargo flow. In order to test the impact of different values of λ and k_0 on the cost in the model, the unbalanced cargo flow ratio (all hubs) is introduced in column 8 of the table. Column 9 represents the selected hub port, and column 9 represents the total cost.

Table 3： Model solution result.

k_0	λ	hub port	hub port cargo volume ratio/%				cargo flow unbalance ratio	Total cost/$10,000
			$H1$	$H2$	$H3$	$H4$		
3	0.4	1，2，3	10.24	22.85	58.29	—	5.69	225.90
	0.6	1，2，4	14.78	25.93	62.78	—	4.25	458.76
4	0.4	1，2，3，4	11.63	18.42	28.67	48.59	4.18	249.75
	0.6	C，2，3，4	15.89	14.76	27.04	47.83	3.24	356.68

When k_0 is fixed, the total transportation cost shows an increasing trend as k_0 decreases, indicating that the size of the discount factor is very important to the expected cost of the entire network. At the same time, λ also affects the balance of the cargo flow. When λ takes a small value, that is, when the discount is very strong, because the whole system tends to use the scale effect, the cargo flow will tend to concentrate on several key hub ports. Make the cost of the entire network lower.

When λ is fixed, as k_0 increases, the transportation cost of the network decreases. Because when building more hub ports, on the one hand, feeder ports far from the hub ports are not forced to make a detour to transport goods; on the other hand, the increase in hub ports can better balance the flow of goods, make the traffic distribution of the whole network more reasonable.

5 CONCLUSION

From the perspective of shipping companies, this paper considers the effects of partial and complete port failures in hub-and-spoke shipping networks. As the core element of the network, the hub port will bring immeasurable cost losses to shipping companies once congestion occurs. Therefore, we consider the problem of hub port congestion, improve the emergency management capabilities of shipping companies, and optimize the hub-and-spoke shipping network system under congestion. This paper solves the optimization problem of a single-distribution hub-and-spoke shipping network considering the congestion of hub ports, adds a congestion cost function to the objective function of port location selection, and solves the mixed-integer nonlinear programming problem employing simulation experiments. The experimental results show that the simulation method can quickly and effectively verify the correctness of the model and realize the target optimization quickly.

The next step of the study is to take into account the possibility of port failure during shipping network planning, considering the use of improved heuristics to solve large-scale hub-and-spoke shipping network optimization problems. In addition, many hub-and-spoke shipping networks are multi-distribution models or other hybrid hub-and-spoke networks, and this paper only considers the possibility of hub port failure. In practice, there will also be the possibility of feeder port failure. Therefore, future research can also consider the improvement scheme of feeder port failure in other types of networks.

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