A Study on the Optimization of Regional Port Investments Considering Disasters under Uncertain Demand

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Abstract. As a key link in the maritime supply chain, reasonable investment in ports can enhance the location advantages of the hinterland. In this paper, the investment problem of multi-port areas considering disasters under uncertain demand is studied, an optimisation model is established with the objective of minimizing the total system cost and maximising the efficiency of port operations, and an analysis of the port cluster in the Yangtze River Delta region is carried out to obtain an investment plan for the port cluster with reasonable results. This investment optimization can provide some reference for government investment in the construction of ports.

Keywords- Port investment, uncertainty of demand, disaster prevention, multi-objective optimisation

1. Introduction

As an important basic industry in the national economic system [1], reasonable investment in ports can effectively enhance the location advantage of the hinterland. Demand is an important basis for port investment decisions, and a changing market can cause a certain gap between the port's capacity and actual freight demand after construction [2]. At the same time, ports are often affected by natural disasters, with the risk of disruption and damage to facilities. Therefore, a study on port investment considering disasters under the uncertainty of demand would be beneficial to improve the overall strength of the port and enhance the competitiveness of the region's port cluster.

At present, port capacity investment and disaster prevention investment have attracted extensive attention from scholars at home and abroad. For the problem of capacity investment under uncertain demand, ZHAO [2] used geometric Brownian motion to describe the uncertainty of demand and studied the port investment decision problem in multi-port areas. ZHENG [3] used the real options approach to analyze a study on the timing of terminal investment decisions considering competitors in an uncertain market. CHEN [4] established a two-stage game to study the problem of simultaneous investment in the expansion of two risk-averse ports, taking into account uncertain market demand and port congestion. YANG [5] used a two-firm oligopoly option game model to study the optimal investment strategy of two firms, assuming uncertainty in investment costs and market demand. XIAO [6] considered the uncertainty of disaster occurrence, the return on investment in prevention, and the timing of investment to develop an

ICBBEM 2023, May 19-21, Hangzhou, People's Republic of China

DOI 10.4108/eai.19-5-2023.2334364

economic model to analyze investment in disaster prevention in ports. ZHENG [7] studied the impact of two common policies, minimum requirement regulations and subsidy policies, on investment in port adaptation. GONG [8] consider a theoretical study of the rational allocation of resources between the two types of investments in a given port in the presence of uncertainty in both disasters and demand.

A review of the current port investment field reveals that the issue of port investment under conditions of demand uncertainty has received increasing attention from scholars. Most of the studies on investment in natural disaster prevention are focused on individual ports or terminals and ignore the impact of disaster events and investment in prevention on port capacity. Based on this, this paper takes a regional port as the object of research and considers the investment optimization of port clusters under uncertain demand and disaster occurrence.

2. Problem description

The problem studied in this paper involves two main stakeholders, the cargo owner and the port investment operator, whose relationship is shown in 'Figure 1'.

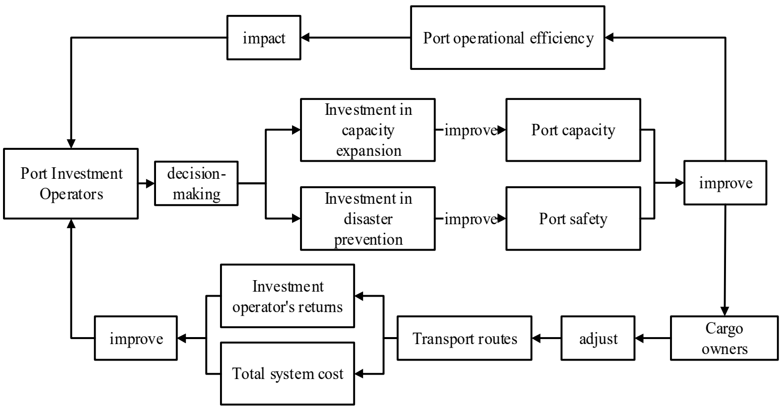

Figure 1. Interaction between cargo owners and investment operators

In the above relationship, the cargo owner makes the transport route and chooses the port for loading and unloading from the perspective of his own interests; the port investment operator makes two investment decisions from the perspective of system optimality; and the two influence each other until equilibrium is reached. The investment optimization objective of this paper is to optimize the total cost of the system and the operational efficiency of the port, while ensuring the basic profitability of the port investment operator, in order to achieve the coordinated development of ports in the region and the effective use of resources.

The model parameters involved in the research questions in this paper and their implications are shown in Table 1.

Table 1. Variable Description

Variable	Definition
N	Collection of port nodes, $i \in N$
A	Collection of hinterland demand nodes, $a \in A$
S	Hinterland freight demand scenario set, u_s
Ω	All hazards intensity scenario set, $\omega \in \Omega$
B	Total funding budget
I_i	Port i for investment in capacity expansion
V_i	Port i funds for disaster prevention investments
x_{ai}^s	Volume of containers shipped from hinterland a to port i under demand scenario s
c_{ai}	Land transport costs per unit container per unit distance
l_{ai}	Actual transport distance from node a to node i
μ_{ai}	Land transport time cost conversion parameters
c_i	Unit container handling costs at port i
μ_i	Port berthing time cost conversion parameters
t_{i0}	Service hours at port i when there is no congestion
q_i	Throughput of port i during the planning period
K_i	Port i capacity after investment in capacity expansion
K_0	Original throughput capacity prior to port i investment
T	Number of disasters expected to occur during the investment period
R	Indicates the extent of damage to the port
$R^{'}$	Preventing the extent of damage to the port after investment
M_ω	Mean value of damage to the port for a disaster intensity of ω
$\phi(V_i / K_i)$	Indicates the vulnerability of the port in the event of a disaster, $\phi(V_i / K_i) = R(V_i / K_i)^{-1}$
H_a^s	Freight demand in hinterland a under demand scenario s
$\alpha_{\exp}$	Expected rate of return on port investments

3. Model

The regional port investment optimization problem considering disasters under demand uncertainty constructed in this paper can be abstracted as the following model:

$$\min C = \sum_{s \in S} u_s C_s(x) \tag{1}$$

$$C_s(x)=\sum_{i\in N}\sum_{a\in A}\left(c_{ai}l_{ai}x_{ai}^s+\frac{l_{ai}}{v}\mu_{ai}x_{ai}^s\right)+\sum_{i\in N}\sum_{\omega\in\Omega}\left\{x_{ai}^s c_i+\mu_i x_{ai}^s t_{i0}\left[1+\alpha_1\left(\frac{q_i}{(1-R^{'})K_i}\right)^{\alpha_2}\right]\right\}$$
$$+\sum_{i\in N}I_i+\sum_{i\in N}V_i+\sum_{i\in N}\sum_{\omega\in\Omega}\varepsilon(\omega)\cdot T\cdot K_i\cdot\phi\left(\frac{V_i}{K_i}\right) \tag{2}$$

$$\min W=\sum_{a\in A}\sum_{i\in N}\sum_{\omega\in\Omega}u_s\left|\frac{\sum_{a\in A}x_{ai}^s}{(1-R^{'})K_i}-1\right| \tag{3}$$

$$\sum_{i\in N}I_i+\sum_{i\in N}V_i\le B \tag{4}$$

$$\sum_{i\in N}\left\{x_{ai}^s c_i+\mu_i x_{ai}t_{i0}\left[1+\alpha_1\left(\frac{q_i}{((1-R^{'}))K_i}\right)^{\alpha_2}\right]\right\}\ge\alpha_{\exp}(\sum_{i\in N}I_i+\sum_{i\in N}V_i),i\in N,s\in S,\omega\in\Omega \tag{5}$$

$$\sum_{a\in A}x_{ai}^s\le(1-R^{'})K_0[1+\beta_1 I_i^{\beta_2}],i\in N,s\in S,\omega\in\Omega \tag{6}$$

$$K_i=K_0[1+\beta_1 \mathrm{I}_i^{\beta_2}] \tag{7}$$

$$R^{'}=K_i\cdot\phi\left(\frac{V_i}{K_i}\right)R/M_\omega,\omega\in\Omega,i\in N \tag{8}$$

$$\mathrm{H}_a^s=\sum_{i\in N}x_{ai}^s,a\in A,s\in S \tag{9}$$

$$\sum_{s\in S}u_s=1 \tag{10}$$

$$I_i\ge 0,\ V_i\ge 0,\ q_i\ge 0,\ x_{ai}^s\ge 0 \tag{11}$$

Equation (1) and Equation (3) are the objective functions in the model. Equation (1) represents the minimum total system cost, and the specific cost components are shown in equation (2). Total costs include shipper's land transport costs, land transport time costs, port handling costs, in-port time costs, port operator's investment expansion costs, and damage costs in the event of a disaster at the port. Equation (3) is the maximum efficiency of port operation. Equation (4) to (11) are the constraints of the model. Equation (4) is the financial constraint; Equation (5) is the expected return constraint for port investments. Equation (6) represents the port throughput capacity constraint; Equation (7) represents the throughput capacity after investment in port capacity; Equation (8) is the extent of damage to the port following the investment in disaster prevention, the port passage capacity after a disaster is $(1-R)K_i$, the port throughput capacity in the event of a disaster in the port after investment in disaster prevention is $(1-R^{'})K_i$; Equation (9) ensures that cargo can be shipped at each demand point under the scenario. Equation (10) represents the probability that all demand scenarios occur with a probability of one; Equation (11) is the non-negative constraint in the model.

4. Example analysis

1.1. 4.1 Data collection and collation

This paper assumes construction investment in six representative ports in the Yangtze River Delta region in 2021, with a five-year planning period and a total government investment budget of RMB 10 billion. Thirty-four nodal cities in Shanghai, Zhejiang, Jiangsu, and Anhui provinces were selected as port hinterlands. In order to maximize coverage of all possible scenarios, the average freight volume at each node was set as the benchmark, and the scenarios were classified using 50% below average, 25% below average, average, 25% above average, and 50% above average, with some regional demand settings shown in Table 2. The probability of occurrence for each scenario was set at 0.1, 0.1, 0.2, 0.3, and 0.3. In this paper, taking wind damage as an example, Table 3 shows the value settings regarding disasters.

Table 2. Freight demand in selected hinterland cities under various demand scenarios

Unit: TEU

Region	Hinterland Cities	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Shanghai	Shanghai	16015500	24023250	32031000	40038750	48046500
Jiangsu Province	Nanjing	1213750	1820625	2427500	3034375	3641250
	Zhenjiang	221500	332250	443000	553750	664500
	Yangzhou	258500	387750	517000	646250	775500
	Changzhou	231500	347250	463000	578750	694500
	Suzhou	2487350	3731025	4974700	6218375	7462050
	Nantong	913000	1369500	1826000	2282500	2739000
Zhejiang Province	Hangzhou	157500	236250	315000	393750	472500
	Jiaxing	529650	794475	1059300	1324125	1588950
	Shaoxing	82500	123750	165000	206250	247500
	Ningbo	9368750	14053125	18737500	23421875	28106250
	Jinzhou	210500	315750	421000	526250	631500
	Taizhou	251000	376500	502000	627500	753000
Anhui Province	Hefei	192750	289125	385500	481875	578250
	Wuhu	563250	844875	1126500	1408125	1689750
	Chuzhou	77500	116250	155000	193750	232500
	Maanshan	93500	140250	187000	233750	280500
	Xuancheng	95000	142500	190000	237500	285000

Table 3. Parameter settings regarding disasters

Disaster level	Type of damage	Wind speed / (m/s)	Wind Level	Extent of port damage	Probability interval
1	Minor losses	10.8–17.1	Level 6-7	0.3	(0，0.5)
2	Larger losses	17.2–24.4	Level 8-9	0.6	(0，0.44)
3	Serious losses	24.5–32.6	Level 10-11	0.8	(0，0.43)
4	Extraordinary losses	>32.6	Level 12 and above	1	(0，0.67)

1.2. 4.2 Results and analysis

The case data was brought into the model, and the non-dominated sorted genet-ic algorithm-II (NSGA-II) was chosen to program the solution in MATLAB 2020b. The convergence of the objective function optimization obtained is shown in Figure 2 and Figure 3. The investment optimization results for the port are shown in Table 4.

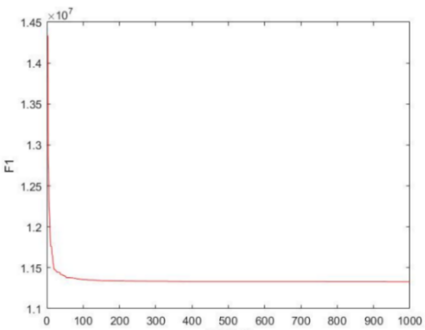

Figure 2. Objective function 1 optimization convergence diagram

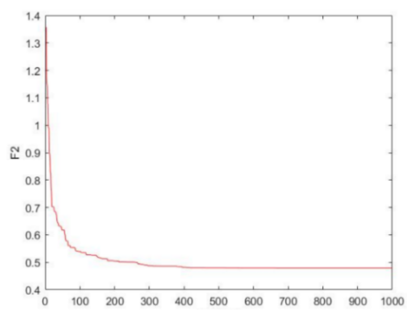

Figure 3. Objective function 2 optimization convergence diagram

According to the investment results, it is seen that the total system cost of the Yangtze River Delta port cluster after investment optimization is $1.13*10^7$ RMB and the operational efficiency of the port cluster is 52.2%. The Yangtze River Delta port cluster's investment targets are mainly Shanghai Port and Ningbo Zhoushan Port, both of which have higher investment amounts, while all other ports are at a lower level. This correlates with the size of the ports in Shanghai Port and Ningbo Zhoushan Port. It can also be seen that the amount of investment in capacity for each port is higher than the investment in disaster prevention. This is because investment in disaster prevention is only beneficial when a disaster occurs, so ports are more willing to invest in port capacity to expand the port's throughput capacity. Throughput forecast, Shanghai port is expected to reach 40.89 million TEU and Ningbo Zhoushan port will reach 32.53 million TEU during the planning period, while the port's passing capacity after investment is still insufficient, so relevant measures should still be taken to improve the utilization rate of shoreline and accelerate the construction of port infrastructure.

Table 4. Port Cluster Investment Optimization Results

	Shanghai Port	Ningbo Zhoushan Port	Lianyungang Port	Suzhou Port	Nanjing Port	Jiaxing Port
Investment in capacity expansion(billion)	32.1	23.0	6.4	5.1	6.1	1.9
Investment in disaster preparedness(billion)	16.4	15.8	5.5	1.5	3.5	1.6
Port Capacity (million TEU)	4186	2565	348	591	211	140

5. Conclusion

This paper constructs a port investment decision problem considering uncertainty in demand and disaster occurrence, combines the influence of a limited government budget, establishes a dual-objective optimisation model with minimum total system cost and maximum port cluster utilisation, and designs a genetic algorithm-based solution. The model integrates factors such as investment returns, resource budgets, and passing capacity under disaster conditions. Six representative ports in the Yangtze River Delta region are used as examples for solution analysis, and the solution for investment in port clusters is obtained with reasonable results. The proposed disaster prevention investment can provide some reference value for the government's subsequent investment in construction. The optimization of multi-phase investment in port clusters can be considered in the future to enrich the theory of port investment.

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