Research on Emergency Management of Marine Rescue Site Selection

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Abstract. With the increasing of maritime trade, the frequency of maritime emergencies is also increasing. In order to improve the rescue efficiency and shorten the response time of Marine rescue, this paper studies the location and resource allocation of Marine rescue station. In this paper, a two-stage stochastic planning location model with minimum total cost is established, the historical data is processed by K-means clustering analysis, and the randomness of maritime accident points is considered by Monte Carlo simulation method. The validity and rationality of the model and the algorithm are proved by taking the relevant data of the Bohai Sea and the Yellow Sea of China as examples. This study can provide a certain reference direction for the site selection and resource allocation of Marine emergency rescue in China's coastal cities.

Keywords: Site selection of rescue station, Monte Carlo simulation, Stochastic programming, Coastal city rescue

1 INTRODUCTION

With the rapid development of China's economy and the continuous increase of maritime trade, safety accidents occur frequently in coastal cities, and the importance of maritime rescue is becoming increasingly prominent. The unpredictability and potential dangers of maritime emergencies require swift and effective rescue operations. This study optimizes rescue location and resource allocation through sea and air coordination strategies, including the layout of traditional rescue forces such as ships and helicopters, and the integration of rescue resources in coastal cities. The comprehensive approach aims to provide innovative perspectives and practical solutions for emergency management, enhance the role of coastal cities in maritime rescue systems, and ensure the safety of people and the protection of the Marine environment.

At present, many scholars have conducted research on the issue of maritime rescue stations from different perspectives, mainly focusing on three aspects: only considering the site selection of maritime emergency facilities, only considering the allocation of maritime emergency rescue materials, and comprehensively considering the site selection and resource allocation at sea.

In the study that only considers the location of Marine emergency facilities, in 2017,

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Chen M[1] proposed the NSGA II solution algorithm based on the alternate coverage location model of time satisfaction to determine the number of Marine emergency rescue sites. In 2019, Shan Y [2]established a rescue base location model in the Arctic sea based on three models: set coverage model, double repeat coverage model and P-median model, and took P-median model as the core, realizing full coverage of rescue areas and multiple repeat coverage of high-risk areas. In 2019, Xiao Z[3] studied the location of the Marine search and rescue base, selected the island as the Marine search and rescue base, collected accident data and relevant data of rescue ships, established the maximum coverage model and solved it, and the result was greatly improved compared with the current coverage of rescue sites. The above location model only studies the ship rescue site, ignoring the layout optimization of the rescue helicopter site, which will result in unreasonable layout.

In the study that only considers the allocation of emergency relief materials, in 2016, Razi N [4]et al. studied the allocation of maritime relief materials in the Aegean Sea based on analytic hierarchy process (AHP) and K-means clustering algorithm, aiming at the minimum of total deviation and delay. In 2019, Guo Y[5] et al. proposed a multi-objective integer nonlinear programming model for resource allocation in long-distance maritime search and rescue, and proposed two innovative objectives: maximizing task completion possibility and maximizing resource utilization. In 2020, Lecai Cai[6] et al. considered the joint configuration of search and rescue ships and aircraft in the allocation of Marine emergency resources, established a dual-layer mixed integer programming model, and used genetic algorithm and particle swarm optimization algorithm to solve the problem. In terms of the allocation of rescue forces, most scholars ignore the location of Marine rescue sites and helicopter rescue.

In the study of integrated optimization of offshore location allocation resources, in 2015, AIF[7] studied the location-allocation-allocation problem of emergency resources in Marine emergency response system based on the maximum coverage model, proposed a discrete nonlinear integer programming model integrating positioning, allocation and allocation problems, and designed a hybrid algorithm of heuristic algorithm and genetic algorithm. In 2018, Akbari[8]A took into account the impact of ship rescue capacity and speed when solving the problem of location selection of maritime rescue sites, and established a multi-objective planning model based on three objectives: initial coverage, multiple coverage and response time. Compared with the traditional location allocation model, the response time and coverage have been greatly improved. In 2020, Jin Yiq[9] combined GIS technology to design a multi-objective plant growth simulation algorithm in the process of selecting rescue bases and allocating rescue ships in remote sea areas, and considered islands as candidate points for rescue bases to improve rescue efficiency and provide new analysis methods and optimization schemes for remote sea rescue base selection and ship allocation. The above studies mostly focus on the deterministic studies of ship site selection and ship configuration, but ignore the advantages of helicopter rescue in sea rescue, resulting in unreasonable layout and configuration. In this paper, k-means clustering and Monte Carlo simulation optimization are combined to carry out Marine rescue, which can effectively divide high-risk areas, simulate accident randomness, and significantly improve rescue efficiency. Based on the historical accident data at sea, this paper uses Monte Carlo simulation method to conduct random simulation of Marine accidents, and conducts joint research on Marine ship station and helicopter station.

The contribution of this paper is mainly reflected in the following aspects;

(1) Monte Carlo simulation is used to consider the randomness of the point space of demand for salvage at sea.

(2) The site selection and resource allocation of rescue ship station and rescue helicopter station are considered comprehensively.

(3) Considering different types of rescue ships and rescue helicopters, a two-stage stochastic planning model is established and verified by data examples in the Bohai Sea and the Yellow Sea, which provides certain opinions and suggestions for the emergency rescue of coastal cities in China.

2 PROBLEM DESCRIPTION

In this paper, from the perspective of sea and air cooperation, integrated optimization research is carried out on the site selection and rescue force allocation of Marine emergency rescue stations, so as to ensure that the rescue ship and rescue helicopter stations can provide more efficient rescue when dangerous situations occur. This paper aims to minimize the total cost to determine the rescue location of the rescue site and the number of rescue forces. The location and time of future maritime accidents are uncertain. By considering the spatial randomness of demand points, the location of stations and the size of rescue force equipment configured can be more reasonable, so as to achieve comprehensive coverage of water areas and multiple repeated coverage of key waters, shorten rescue time and improve rescue efficiency.

This paper considers three kinds of rescue vessels, including rescue speedboat, offshore fast rescue vessel and large ocean rescue vessel. According to the salvage capacity of ships, it is stipulated that large ocean-going salvage vessels can sail in all navigation areas, offshore fast rescue vessels can sail in offshore waters, and rescue speedboats can only sail in coastal waters.

3 MODEL FORMULATION

3.1 Model Assumptions

The assumptions of the maritime rescue site selection and rescue force allocation model constructed in this paper from the perspective of air-sea collaboration are as follows:

(1) The centroid of each region after k-means clustering is used as the candidate point of maritime ship rescue site.

(2) The construction cost of each type of rescue site and rescue equipment is known.

(3) The needs of an accident point can be distributed to multiple rescue sites.

(4) A rescue site can provide rescue services for multiple accident demand points.

(5) The maximum rescue distance of each ship and helicopter is known.

3.2 Description of Symbols

The parameters of the model are defined as: a,b denotes candidate ship sites and helicopter sites; j , k denotes the types of rescue ships and rescue helicopters respectively; c stands for accident demand point at sea; c_a, c_bConstruction cost of ship station and helicopter station;D_j,D_k, Cost of configuring Ship j and helicopter k;O_j,O_kOperating costs of ship type j Helicopter type k;G_{cs}Unmet penalty costs at accident point c under scenario s;F_j,F_k, Unit navigation cost of ships and helicopters; H_j,H_k, Unit delay cost of ships and helicopters; R_j,R_kThe rescue capability of ship type j and helicopter type k;T_{acjs}^B denotes the journey time of sending resource type j from ship rescue station a to respond to accident point c; T_{bcks}^H denotes the flight time of resource type k dispatched from helicopter rescue station b to respond to incident point c; T_{max}^B, T_{max}^HMaximum rescue time by ship and helicopter;Q_{cs} denotes the demand for accident point c in scenario s;u_{CS} denotes the unmet demand at accident point c under scenario s;p_s denotes the probability of occurrence of scenario s; n_{acjs}^B denotes the number of ship resources of type j dispatched from ship rescue site a to accident point c under scenario s; n_{bcks}^H represents the number of helicopter resources of type k dispatched from helicopter rescue site b to accident point c under scenario s;L_j,L_kIndicates the farthest rescue distance between Class j and Class k rescue equipment;

The decision variable is defined as: x_a denotes the establishment of a site at the candidate point a of the ship rescue site, otherwise 0; x_bIndicates that a helicopter rescue station is set up at location b, otherwise 0; x_{aj} denotes the number of ships of type j assigned at vessel salvage site a; y_{bk} denotes the number of helicopter types k assigned at helicopter rescue site b; z_{acjs}^B a binary variable indicating whether the dispatch of ship resource type j from ship rescue site A to accident point c occurred; z_{bcks}^H denotes A binary variable indicating whether the dispatch of helicopter resource type k from helicopter rescue site b to accident point c occurred;

3.3 Mathematical Model

Objective function:

$$Minimize\sum_{a\in A}C_a x_a+\sum_{b\in B}C_b x_b+\sum_{a\in A}\sum_{j\in J}(D_j+O_j)\ y_{aj}+\sum_{b\in B}\sum_{k\in K}(D_k+\mathrm{O}_k)y_{bk}+\sum_{s\in S}p_s$$

$$\left(\sum_{a\in A}\sum_{c\in C}\sum_{j\in J}(F_j n_{acjs}^B T_{acjs}^B+H_j n_{acjs}^B(\mathrm{T}_{\mathrm{acjs}}^B-\mathrm{T}_{\mathrm{max}}^B)+\sum_{b\in B}\sum_{c\in C}\sum_{k\in K}(F_k n_{bcks}^H T_{bcks}^H+H_k n_{bcks}^H(T_{bcks}^H-\mathrm{T}_{\mathrm{max}}^H)+\sum_{c\in C}G_{cs}u_{cs}\right)$$

Restrictive condition:

$$\sum_{a\in A}x_a\geq 1 \tag{1}$$

$$\sum_{b\in B}x_b\geq 1 \tag{2}$$

$$\sum_{a\in A} y_{aj} \le T_j, \forall j \tag{3}$$

$$\sum_{b\in B} y_{bk} \le T_k, \forall k \tag{4}$$

$$\sum_{j\in J} y_{aj} \ge x_a, \forall a \tag{5}$$

$$\sum_{k\in K} y_{bk} \ge x_b, \forall b \tag{6}$$

$$y_{aj} \le Mx_a, \forall a, j \tag{7}$$

$$y_{bk} \le Mx_b, \forall b, k \tag{8}$$

$$y_{aj} = 0,\ \ \forall a \in A_a,\ \ j \in (1,2) \tag{9}$$

$$\sum_{c\in C}\sum_{s\in S} n^B_{acjs} \le y_{aj,} \forall a, j \tag{10}$$

$$\sum_{a\in A}\sum_{j\in J} z^B_{acjs} \ge 1, \forall \mathrm{c}, s \tag{11}$$

$$\sum_{a\in A}\sum_{j\in J} z^B_{acjs} \ge 1, \forall \mathrm{c}, s \tag{12}$$

$$\sum_{b\in B}\sum_{k\in K} z^H_{bcks} \ge 1, \forall c, s \tag{13}$$

$$\sum_{a\in a}\sum_{j\in J} R_j n^B_{acjs} z^B_{acjs} + \sum_{b\in B}\sum_{k\in K} R_k n^H_{bcks} z^H_{bcks} + u_{cs} = Q_{cs} \tag{14}$$

$$n^B_{acjs} \le Mz^B_{acjs}, \forall a, c, j, s \tag{15}$$

$$n^H_{bcks} \le Mz^H_{bcks}, \forall b, c, k, s \tag{16}$$

$$z^B_{\mathrm{acjs}} = 1,\ \ \mathrm{if}\ \mathrm{d}_{ac} \le \mathrm{L}_j, \forall a, c, j, s \tag{17}$$

$$z^H_{bcks} = 1, \mathrm{if}\ d_{bc} \le \mathrm{L}_k, \forall b, c, k, s \tag{18}$$

$$\mathrm{L}_j = \mathrm{V}_{\mathrm{j}} \mathrm{T}_J / 2,\ \ \mathrm{L}_{\mathrm{K}} = \mathrm{V}_k \mathrm{T}_k / 2 \tag{19}$$

Constraints (1)-(2) indicate that at least one ship station and one helicopter station should be established, Constraints (3)-(4) The number of ship and helicopter types configured does not exceed the number owned, Constraints (5)-(6) At least one search and rescue device is assigned to each established station, Constraints (7)-(8) Resources can only be allocated to established sites. Constraints (9) Offshore quick rescue boats can sail in offshore waters, and rescue boats can only sail in coastal waters. Constraints (10)-(11) The use of relief resources must not exceed the amount allocated in the first stage. Constraints (12)-(13) At least one ship station or aircraft station responds to each incident under each scenario, Constraints (14) The number of rescue resources dispatched should meet the needs of the accident site as far as possible, Constraints (15)-(16) Resources are dispatched only if the site responds to an incident in a specific scenario, Constraints (17)-(19) Distance constraints for rescue equipment.

4 CASE STUDY

4.1 Data Collection

This paper adopts the method of case analysis to conduct the experiment. The relevant data of rescue ships and rescue helicopters come from the Beihai Rescue Bureau of the Ministry of Transport, and the data of maritime accident points are collected from China Maritime Search and Rescue Center in the Bohai Sea and Yellow Sea area from 2021-2023. According to the requirements of the national water traffic safety supervision and rescue system layout planning for rescue time, the maximum rescue time is set to 1.5h, and the distribution of specific accident points is shown in Figure 1.

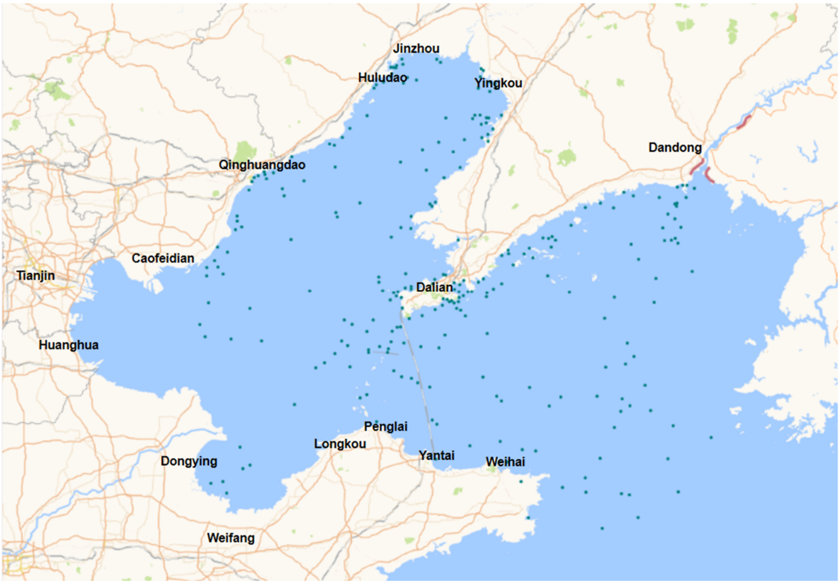

Fig. 1. Distribution of maritime accident points.

The port candidate sites in the Bohai Sea and the Yellow Sea are listed in Table 1 below

Table 1. Candidate sites in the waters around the Bohai Sea.

Number	Port	Longitude and latitude
1	Dalian Port	(121.2°E, 38.80°N)
2	Yingkou Port	(122.2°E, 40.51°N)
3	Jinzhou Port	(121.2°E, 40.95°N)
4	Huludao Port	(120.7°E, 40.50°N)
5	Qinhuangdao Port	(119.6°E, 39.91°N)
6	jingtang Port	(199.2°E, 39.35°N)
7	Caofeidian Port	(118.3°E, 39.20°N)
8	Huanghua Port	(117.8°E, 39.90°N)
9	Huanghua Port	(117.9°E, 38.30°N)
10	Dongying Port	(118.9°E, 38.06°N)
11	Weifang Port	(119.2°E, 37.15°N)
12	Longkou Port	(120.1°E, 37.60°N)
13	Penglai Port	(120.7°E, 37.80°N)
14	Yantai Port	(121.5°E, 37.55°N)
15	Dandong Port	(122.2°E, 37.50°N)
16	Dandong Port	(124.2°E, 39.85°N)

The latitude and longitude of cluster centers after k-means clustering are shown in Table 2

Table 2. Coordinates of centroid points of clustering.

Number	Longitude	latitude	Demand
1	122.2708327	37.6225311	80
2	121.6451161	38.88433457	210
3	121.891321	40.34559307	145
4	121.1408993	39.13969195	105
5	121.0870676	40.77272874	95
6	123.5678786	37.70468709	115
7	118.118497	38.39091911	85
8	119.1291153	38.91397318	85
9	123.9346225	39.55205227	150
10	122.8948952	39.25488777	65
11	120.5408257	39.94946544	45
12	122.2322771	39.12908947	75
13	120.8988595	38.33884806	155
14	117.9167849	38.92684276	125
15	121.4340643	40.76817433	15
16	118.509321	38.91830768	110
17	120.8386435	40.564042	20
18	119.5898829	37.46562489	35
19	119.6766228	39.71725458	95
20	117.7345212	38.79769813	75

The relevant information of various types of rescue vessels and rescue helicopters is shown in Table 3 and Table 4 below.

Table 3. Information about ships.

Ship type	Capacity	Speed/knot	Construction Cost	Operating cost
Small	20	18	50	20
Middle	50	32	80	50
Large	100	22	100	100
Ship type	Delay cost	Penalty cost	Navigation cost	Maximum sailing time
Small	10	20	100	6
Middle	15	20	200	8
Large	8	20	300	M

Table 4. Information about rescue helicopters.

type	Capacity	Speed (km/h)	Construction Cost	Operating cost
Helicopter 1	10	287	30	20
Helicopter 2	20	324	60	30
Ship type	Delay cost	Penalty cost	Navigation cost	Maximum sailing time
Helicopter 1	8	20	200	4.9
Helicopter 2	10	20	400	4.26

4.2 Model Solution

The mathematical model in this paper is a two-stage stochastic programming model with the lowest total cost. Three kinds of rescue ships and two kinds of rescue helicopters are considered in the model. The probability distribution of each region is obtained through cluster analysis using Python. In this paper, the running platform CUP is Intel Core i5-7200U 2.50GHz, the memory is 4GB, and the Gurobi solver version is 10.0.0.

Based on the relevant data of Bohai Sea and nearby waters, the model is solved, and the site selection and configuration of Marine rescue stations are obtained, as shown in Table 5.

Table 5. Results of model solution.

Water area/port name	Small	Middle	Large	Helicopter 1	Helicopter 2
4			1		
6			2		
8			1		
9			1		
11			1		

13			2		
18			1		
Dongying Port	2	2			
Huanghua Port	2	2			
Dalian Port	2	2		2	2
Jingtang Port	2	1			
Penglai Port				2	1
Huludao Port				1	1
Yingkou Port	1	1			
Weihai PORT	2	1			
Tianjin Port	2	1		1	1

The distribution of maritime rescue stations is shown in the following figure 2, The red color in the picture represents the established rescue station.

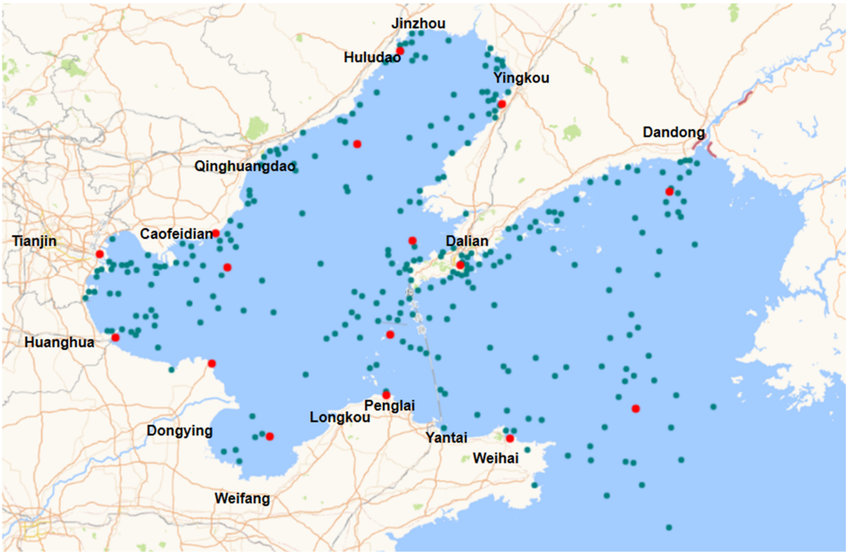

Fig. 2. Distribution of Maritime Rescue Stations.

According to the solution results, 11 rescue helicopters were deployed in four ports: Dalian Port, Huludao Port, Tianjin Port, and Penglai Port. A total of 9 large ocean going rescue ships, 10 nearshore fast rescue ships, and 13 rescue boats were deployed in seven ports and seven water areas, including Yingkou Port, Huanghua Port, Dalian Port, Jingtang Port, Yingkou Port, Weihai Port, and Tianjin Port.

4.3 Sensitivity Analysis of Rescue Time

Rescue response time is crucial to maritime rescue. In consideration of the development needs of China's maritime rescue force, this paper conducts a sensitivity analysis on rescue time T, and the results are shown in Table 6:

Table 6. Sensitivity analysis of rescue time.

Rescue time T/ hour	1	1.5	2	2.5
Small	10	13	12	11
Middle	7	10	9	7
Large	11	9	6	8
Helicopter 1	10	6	5	4
Helicopter 2	8	5	4	3

According to the sensitivity analysis, with the reduction of rescue time, the number of rescue speedboats and offshore fast rescue boats first increases and then decreases, the number of large ocean-going rescue ships gradually increases, and rescue helicopters can only carry out effective rescue within two hours due to the impact of their own flight time. With the reduction of rescue time, the number of helicopters keeps increasing. Attention should be paid to the deployment of rescue helicopters and large ocean-going vessels.

5 CONCLUSION

This paper conducted an integrated study on the site selection and rescue force allocation of maritime rescue sites from the perspective of air-sea collaboration, established a two-stage stochastic planning aiming at the minimum total cost, The main conclusions of this paper are as follows:

(1) Based on the real historical data of the last three years, K-means clustering and Monte Carlo simulation optimization are combined to carry out Marine rescue, which can effectively divide high-risk areas, simulate accident randomness, and significantly improve rescue efficiency.

(2) This paper also considers the site selection and resource allocation of Marine ship and helicopter rescue stations, so that the site selection and allocation of Marine rescue stations are more scientific and reasonable.

(3) The deployment number of rescue equipment under different rescue times can be obtained by improving sensitivity analysis, which can improve certain reference directions for future rescue fleet planning.

Although the research has achieved certain results, there are still some shortcomings. Future studies can further explore the impact of wind and waves on ship speed, and consider including merchant ships in the rescue force to shorten response time and improve rescue efficiency.

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