Key factors analysis of maritime patrol in maritime safety management based on fuzzy analytic hierarchy process

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Abstract: Maritime patrol is a vital part in maritime safety management. In order to improve the maritime patrol quality and have a better implementation of IMO convention, the fuzzy analytic hierarchy process (F-AHP) is used to analyse and identify the key factors of maritime patrol, and provide technical support for the subsequent fuzzy comprehensive evaluation of maritime patrol. Comprehensive expert survey finds key factors of maritime patrol, and builds an analytic hierarchy model. The index system is divided into several subsystems and sub-modules for research, and then qualitative evaluation is converted into quantitative data and the synthetic weight of each element is obtained through judgment matrix and weight calculation. The results show that the five key factors, completion of planned patrol mileage, time consumed for restoration of navigation order, number of complaints about maritime patrol, normal usage of AIS on ships in the area, main area patrol frequency are identified as key safety elements in maritime patrol.

1. Introduction
Maritime patrol can maintain the order of navigation, guarantee maritime safety and security, prevent the ship pollution, and prepare for the emergency responding, which are all required in maritime convention. In 2021, China will accept mandatory supervision for maritime convention implementation by IMO. As maritime patrol is a significant measure to improve the ability to implement the convention, China attaches importance to the evaluation of maritime patrol.

At present, combined with patrol vessels, patrol vehicles (used mainly in inner land waterway), patrol aircraft, VTS (vessel traffic service), and CCTV (closed circuit television) and methods, maritime patrol is more effective and efficient than before, especially after the electronic patrol is applied. The GIS (geographic information system) platform, and the maritime data centre, which are the core part for electronic patrol, makes the data collecting and data analyzing more available. Actually, modern maritime patrol is an advanced multi-perspective way for both law enforcement and maritime service.

Maritime patrol quality, is the extent of the realization of maritime goal, through making detailed plan, using information technology, performing standard law enforcement behaviors, to complete basic patrol task, improve maritime service, and implement the IMO convention.

Traditional way of evaluation is simple and partially effective. Finding key factors can assist maritime administration in having a better understanding of the different parts of maritime patrol and making a detailed plan to push forward the daily patrol task. Through the research of characteristic of maritime patrol, and former study and practical experience, this paper gives the definition of maritime
patrol, and proposes 4 categories (including 14 factors) index. By using the fuzzy analytic hierarchy process, key factors in maritime patrol is identified and subsequent measures can be adopted to improve the maritime patrol quality.

2. Evaluation method

Analytic hierarchy process is a multi criteria decision analysis method combining qualitative and quantitative analysis. The analytic hierarchy process is to decompose the overall responsible system layer by layer, divide the whole into multiple target levels, compare the relative importance between the two influencing factors layer by layer, and form the evaluation matrix of the lower element to the upper element, and then further solve the evaluation matrix.[1] The maximum eigenvalues and corresponding eigenvectors are normalized, and the values of the importance weights of the upper-level elements corresponding to each level of elements are known. Weighted layer by layer according to the weight of each layer, the purpose is to determine the total target weight. Finally, the system analysis is attributed to the determination of the relative importance weight of the lowest layer relative to the highest layer or the ranking of the relative priority order.[2]

2.1. Establishing hierarchical structure

Establishing a hierarchical structure is the most basic step and the most important step, dividing the factors involved in the target problem into different levels. Clearly and clearly divide the various factors and subordinate levels. [3] The target layer is the highest layer.

2.2. Constructing judgment matrix

The judgment matrix is an important basis for calculating the priority weight of each element. By constructing a judgment matrix, a certain element of the upper layer is used as a judgment criterion, and the elements of the next layer are compared in pairs, and the values of the elements in the matrix are determined.

The elements of the previous layer, $E_h$, dominate the elements of the next layer, $A_1, A_2, A_3, \ldots, A_n$, giving them weight, $a_{ij}$, according to their importance.

$$
\begin{bmatrix}
E_h & A_1 & A_2 & \ldots & A_j & \ldots & A_n \\
A_1 & a_{11} & a_{12} & \ldots & a_{1j} & \ldots & a_{1n} \\
A_2 & a_{21} & a_{22} & \ldots & a_{2j} & \ldots & a_{2n} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
A_i & a_{i1} & a_{i2} & \ldots & a_{ij} & \ldots & a_{in} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
A_n & a_{n1} & a_{n2} & \ldots & a_{nj} & \ldots & a_{nn}
\end{bmatrix}
$$

$A_{ij}$ in matrix $A$ means the relative importance of elements $A_i$ to $A_j$ according to $E_h$.

$$
a_{ij} = \frac{w_i}{w_j}
$$

In this paper, the quantile scale method is used to describe the judgment value, and the judgment value is compared with each other to obtain the corresponding judgment matrix.

| Scaling | Meaning                              |
|---------|--------------------------------------|
| 1       | The former and the latter are of the same importance |
The former is slightly more important than the latter
The former is obviously more important than the latter
The former is strongly more important than the latter
The former is extremely more important than the latter
The median value of judgment for two adjacent element

2.3. Using matrix to calculate weight
After the judgment matrix is obtained, the weight calculation can be performed. Judgment matrix
\[ A = (a_{ij})_{n \times n}, \quad a_{ij} > 0, \quad a_{ij} = 1 / a_{ji}, \quad i = 1, 2, 3...n, \quad a_{ii} = 1. \]

The ranking weight of each index is \( W \), and conduct a consistency check.
\[ AW = \lambda_{\text{max}} W. \]

The method to calculate \( W \) is as followings:
(1) Multiply the elements in \( A \) by rows:
\[ u_j = \prod_{i=1}^{n} a_{ij} \]
(2) Extract each root of the outcomes above:
\[ u_i = \sqrt[n]{u_{ij}}. \]
(3) And then perform the following process:
\[ w_j = u_j \left[ \sum_{i=1}^{n} u_i \right]^{-1} \]
(4) The last step is:
\[ \lambda_{\text{max}} = \sum_{i=1}^{n} \left[ (Aw) / nw_i \right] \]

2.4. Consistency test of the judgment matrix
\[ CI = \left( \lambda_{\text{max}} - n \right) / (n - 1). \]

When \( A \) is a complete consistency matrix, \( \lambda_{\text{max}} = n \), the rest eigenvalue are all 0. Generally, \( \lambda_{\text{max}}, \) a single root, more than or equal with \( n \), the rest eigenvalue are close to 0. Under this condition, The weight vector \( W \) obtained by the eigenvalue method is basically in line with reality.

When CR<0.1, it is considered that the consistency of the judgment matrix is acceptable, and the weights can be used; otherwise, it is necessary to re-collect data or adjust the discrete fuzzy sets until the resulting judgment matrix meets the consistency inspection requirements. The current commonly used values are shown in Table 2.

| n  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| RI | 0  | 0  | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 | 1.49 | 1.52 | 1.54 | 1.56 |
3. Analytical Hierarchy Process

3.1. Data source
Owing to the uncertainty of the assessment object and the incompleteness of the data, the method, expert investigation, including discussion and forums, is used to acquire data and information. The discrete fuzzy set theory is used to analyse qualitative judgment collected from experts and professors, and then transformed into quantitative data. The relevant experts are as follows:

Expert 1: Professor of Dalian Maritime University, engaged in maritime safety management research for more than 35 years.

Expert 2: Professor of Dalian Maritime University, engaged in maritime safety management research for more than 25 years.

Expert 3: Doctor in Traffic and Transportation Engineering of Guangdong Ocean University, engaged in traffic and transportation engineering more than 10 years.

Expert 4: Director in China maritime safety administration, engaged in maritime safety for more than 33 years.

Expert 5: Captain in China Ocean Shipping(Group) Company, engaged in ocean transportation for more than 30 years.

3.2. Model building
According to results from former research, and the outcomes of expert investigation, the index system is divided into four subsystems: basic data, informatization level[4-5], law enforcement behavior[6], maritime service quality[7], which are divided into different levels, and finally 16 key factors are selected. As shown in Table 3.

| Table 3. The evaluation index system of the Maritime patrol |
|-----------------------------------------------------------|
| **basic data U1**                                         |
| Completion of planned patrol mileage(Completion percentage) V11 |
| area patrol frequency V12                                  |
| Main area patrol frequency P121                           |
| Common area patrol frequency P122                         |
| period patrol frequency V13                               |
| Peak time period patrol frequency per day P131            |
| Night time period patrol frequency P132                   |
| **informatization level U2**                              |
| VTS radar blind space rate V21                            |
| Normal usage of AIS on ships in the area V22             |
| Monitoring coverage rate of CCTV V23                     |
| **maritime service quality U3**                           |
| Daily service quality V31                                 |
| Time of obstruction clearance P411                       |
| Time consumed for restoration of navigation order P412   |
| Time of information release P413                         |
| Emergency responding service quality V32                 |
| Time of emergency responding P421                        |
| Time of accident investigation P422                      |
| Success rate of search and rescue P423                   |
| **law enforcement behavior U4**                           |
| Number of complaints about maritime patrol V41           |
4. Identification of key factors
By establishing AHP model of the maritime patrol index system, referring to expert discussions, factor importance for maritime patrol in the model are compared and assessed. And the fuzzy AHP is used to identify the key factors. Each expert view has the same weight, since all five experts have equivalent qualifications. Exactly, the expert standardized weights \((C_1, C_2, C_3, C_4, C_5)\) are \((0.20, 0.20, 0.20, 0.20, 0.20)\).

4.1. Calculation process
In the AHP model, there are four factors under the target layer, basic data, informatization level, law enforcement behavior, maritime service quality. The paired comparison results obtained through the comprehensive expert investigation are shown in following tables.

| Table 4. W-U judgment matrix |
|-----------------------------|
| \( W \) | \( U_1 \) | \( U_2 \) | \( U_3 \) | \( U_4 \) | \( a \) |
| \( U_1 \) | 1 | 3 | 1 | 3 | 0.381 |
| \( U_2 \) | 1/3 | 1 | 1/3 | 3 | 0.167 |
| \( U_3 \) | 1 | 3 | 1 | 2 | 0.345 |
| \( U_4 \) | 1/3 | 1/3 | 1/2 | 1 | 0.107 |

\[ \lambda_{\text{max}} = 4.2325 \quad RI = 0.9 \quad CI = 0.0775 \quad CR = 0.0861 < 0.1 \]

| Table 5. U1-V1i judgment matrix |
|---------------------------------|
| \( U_1 \) | \( V_{11} \) | \( V_{12} \) | \( V_{13} \) | \( a \) |
| \( V_{11} \) | 1 | 2 | 3 | 0.539 |
| \( V_{12} \) | 1/2 | 1 | 2 | 0.297 |
| \( V_{13} \) | 1/3 | 1/2 | 1 | 0.164 |

\[ \lambda_{\text{max}} = 3.0055 \quad CI = 0.0028 \quad RI = 0.58 \quad CR = 0.0048 < 0.1 \]

| Table 6. U2-V2i judgment matrix |
|---------------------------------|
| \( U_2 \) | \( V_{21} \) | \( V_{22} \) | \( V_{23} \) | \( a \) |
| \( V_{21} \) | 1 | 1/3 | 1 | 0.192 |
| \( V_{22} \) | 3 | 1 | 4 | 0.634 |
| \( V_{23} \) | 1 | 1/4 | 1 | 0.174 |

\[ \lambda_{\text{max}} = 3.0092 \quad CI = 0.0046 \quad RI = 0.58 \quad CR = 0.0079 < 0.1 \]
### Table 7. U3-V4 judgment matrix

| U3 | V31 | V32 | a  |
|----|-----|-----|----|
| V31| 1   | 2   | 0.667 |
| V32| 1/2 | 1   | 0.333 |

\[ \lambda_{\max} = 2 \quad CI = 0 \quad RI = 0 \quad CR = 0 < 0.1 \]

### Table 8. V12-P12 judgment matrix

| V12 | P121 | P122 | a  |
|-----|------|------|----|
| P121| 1    | 4    | 0.800 |
| P122| 1/4  | 1    | 0.200 |

\[ \lambda_{\max} = 2.1785 \quad CI = 0 \quad RI = 0 \quad CR = 0 < 0.1 \]

### Table 9. V13-P13 judgment matrix

| V13 | P131 | P132 | a  |
|-----|------|------|----|
| P131| 1    | 1    | 0.500 |
| P132| 1    | 1    | 0.500 |

\[ \lambda_{\max} = 2 \quad CI = 0 \quad RI = 0 \quad CR = 0 < 0.1 \]

### Table 10. V41-P41 judgment matrix

| V41 | P411 | P412 | P413 | a  |
|-----|------|------|------|----|
| P411| 1    | 1/3  | 2    | 0.252 |
| P412| 3    | 1    | 3    | 0.589 |
| P413| 1/2  | 1/3  | 1    | 0.159 |

\[ \lambda_{\max} = 3.0533 \quad CI = 0.0267 \quad RI = 0.58 \quad CR = 0.0459 < 0.1 \]

### Table 11. V42-P42 judgment matrix

| V42 | P421 | P422 | P423 | a  |
|-----|------|------|------|----|
| P421| 1    | 3    | 2    | 0.539 |
| P422| 1/3  | 1    | 1/2  | 0.164 |
| P423| 1/2  | 2    | 1    | 0.297 |

\[ \lambda_{\max} = 3.0092 \quad CI = 0.0046 \quad RI = 0.58 \quad CR = 0.0079 < 0.1 \]
4.2 Weight calculation at each level

Table 12. Weight of maritime patrol importance

| basic data | informatization level | maritime service quality | law enforcement behavior |
|------------|-----------------------|--------------------------|--------------------------|
| weight     | 0.381                 | 0.167                    | 0.345                    | 0.107                    |

Table 13. Weight of basic data

| Completion of planned patrol mileage (Completion percentage) | area patrol frequency | period patrol frequency |
|-------------------------------------------------------------|-----------------------|-------------------------|
| weight                                                      | 0.539                 | 0.297                   | 0.164                   |

Table 14. Weight of informatization level

| VTS radar blind space rate | Normal usage of AIS on ships in the area | Monitoring coverage rate of CCTV |
|----------------------------|-----------------------------------------|---------------------------------|
| weight                     | 0.192                                   | 0.634                           | 0.174                   |

Table 15. Weight of maritime service quality

| Daily service quality | Emergency responding service quality |
|-----------------------|---------------------------------------|
| weight                | 0.667                                 | 0.333                           |

Table 16. Weight of area patrol frequency

| Main area patrol frequency | Common area patrol frequency |
|----------------------------|-----------------------------|
| weight                     | 0.800                       | 0.200                          |

Table 17. Weight of period patrol frequency

| Peak time period patrol frequency per day | Night time period patrol frequency |
|------------------------------------------|-----------------------------------|
| weight                                  | 0.5                               | 0.5                              |

Table 18. Weight of daily service quality

| Time of obstruction clearance | Time consumed for restoration of navigation order | Time of information release |
|------------------------------|--------------------------------------------------|-----------------------------|
| weight                       | 0.252                                            | 0.589                        | 0.159                       |

Table 19. Weight of emergency responding service quality

| Time of emergency responding | Time of accident investigation | Success rate of search and rescue |
|------------------------------|--------------------------------|----------------------------------|
| weight                       | 0.539                          | 0.160                           | 0.297                        |

Table 20. Weight of law enforcement behaviour

| Number of complaints about maritime patrol |
|--------------------------------------------|
| weight                                     |
| 0.107                                       |

Based on the weights of each level, the synthetic weights of 16 key factors are calculated. The results are shown in Table 21.
Table 21. Synthetic weight of risk factors

| Subordinate level      | Key factors                              | Synthetic weight | Rank |
|------------------------|------------------------------------------|------------------|------|
| basic data             | Completion of planned patrol mileage      |                  |      |
|                        | Completion percentage                     | 0.205            | 1    |
|                        | area patrol frequency                     |                  |      |
|                        | Main area patrol frequency               | 0.091            | 5    |
|                        | Common area patrol frequency             | 0.023            | 14   |
|                        | period patrol frequency                  |                  |      |
|                        | Peak time period patrol frequency per day | 0.031            | 11   |
|                        | Night time period patrol frequency        | 0.031            | 11   |
| informatization level | VTS radar blind space rate                | 0.032            | 10   |
|                        | Normal usage of AIS on ships in the area  | 0.106            | 4    |
|                        | Monitoring coverage rate of CCTV          | 0.029            | 13   |
| maritime service quality | Daily service quality                    |                  |      |
|                        | Time of obstruction clearance            | 0.058            | 7    |
|                        | Time consumed for restoration of navigation order | 0.136 | 2    |
|                        | Time of information release              | 0.036            | 8    |
|                        | Emergency responding service quality      |                  |      |
|                        | Time of emergency responding             | 0.062            | 6    |
|                        | Time of accident investigation           | 0.019            | 15   |
|                        | Success rate of search and rescue        | 0.034            | 9    |
| law enforcement behavior | Number of complaints about maritime patrol | 0.107            | 3    |

It can be seen from the ranking in Table 21 that the five key factors of completion of planned patrol mileage, time consumed for restoration of navigation order, number of complaints about maritime patrol, normal usage of AIS on ships in the area, main area patrol frequency are identified as the top 5 key factors of maritime patrol evaluation, with a total contribution rate of 64.5%. The top five risk factors mainly come from basic data, maritime service quality, law enforcement behavior, informatization level.

5. Conclusions

By applying the Fuzzy-AHP method to the maritime patrol, the AHP model of the maritime patrol index system is established to identify the key factors. In view of the identified key factors, for the purpose to improve the maritime patrol quality, following measures should be adopted. The first is to make up deliberate patrol plan, containing a reasonable patrol route which covers all the high risk area for marine accident and incident. The second is to organize the waterway which is more suitable for navigation, especially in narrow channel and inner land waterway. The third is to enhance the interior training and management, and to standardize the officer’s law enforcement behaviors to minimize the complaints from administrative counterpart. The fourth is to adopt reasonable means to ensure the formal use of AIS equipment on ships in the each area. By such measures, maritime safety condition can be dramatically improved and IMO conventions implementation condition could benefit from such improvement.

In the subsequent study, the author could to use fuzzy comprehensive method to evaluate the maritime patrol quality, the index system built in this essay could be a base for the latter work.
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