The application of multi-level fuzzy comprehensive evaluation of improved analytic hierarchy process in ship safety evaluation

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Abstract. In order to evaluate the safety status of transport ships, a multi-level fuzzy comprehensive evaluation model based on improved AHP (Analytic Hierarchy Process) is proposed. The weight of factors is determined by improved AHP, which effectively solves the problem that the judgment matrix determined by experts with strong subjectivity is difficult to be consistent, and the problem that a large number of single factor information of various risk sources is ignored is reasonably solved by using multi-level fuzzy comprehensive evaluation. This paper conducts the case study on the model. The results show that the model can evaluate the ship safety risk scientifically and reasonably, and provide reference for the ship management company and the maritime bureau to improve the management methods.

1. Introduction

According to reports, in 2018, there were 176 maritime traffic accidents, 83 shipwrecks, 237 people dead and missing, with a direct economic loss of about 290 million yuan. Maritime traffic accidents are often accompanied by a large number of deaths and injuries, with great social harm. How to prevent the occurrence of maritime traffic accidents is an important issue for the China's maritime affairs. Therefore, the purpose of this paper is to develop a set of evaluation methods suitable for the transport ship safety, which can provide a scientific basis for the ship management companies and the maritime bureau. For this reason, this paper first outlines the existing mathematical models of ship safety risk evaluation at home and abroad, and then proposes the potential advantages of using the multi-level fuzzy comprehensive evaluation model of improved AHP. The construction method of the model is given. Finally, an example is used to verify the scientificity and rationality of the model. The multi-level fuzzy comprehensive model of improved AHP can well solve the problem of safety evaluation of transport ships with many risk sources and complex relations, so as to promote the development of maritime traffic safety in China.

2. Overview of safety risk evaluation model of ship

At present, there are mainly grey system method [1], probability theory method [2], neural network method [3-4], analytic hierarchy process [5], fuzzy comprehensive evaluation method [6] and fuzzy comprehensive evaluation method based on AHP[7] for the safety risk evaluation of transport ships, among which the fuzzy comprehensive evaluation method based on AHP integrates the advantages of the two methods and is widely used in the field of complex factor evaluation in recent years. The results
are wonderful. However, when using AHP to determine the weight of each factor, experts have different understanding of the concept. The subjectivity of scoring greatly affects the consistency of the judgment matrix and the scientificity of the weight vector. In order to overcome the above shortcomings, optimize AHP, make the weight vector more objective and scientific, and develop a multi-level fuzzy comprehensive evaluation method based on improved AHP. This method is rarely used in the field of safety risk evaluation of transport ships.

3. Construction of multi-level fuzzy comprehensive evaluation model based on improved AHP

A multi-level fuzzy comprehensive evaluation model based on the improved AHP is developed on the basis of the fuzzy comprehensive evaluation model based on the AHP, so it can adopt the construction method of fuzzy comprehensive evaluation model based on the AHP, which mainly includes the following steps: building a risk evaluation indicator system with clear hierarchy and reasonable structure, establishing factor set and weight set, using the improved AHP method to determine the weight of each hierarchy of indicators [8], using the expert investigation method to establish the membership matrix row of the lowest hierarchy indicator, using the appropriate fuzzy operator to calculate the membership degree of upper hierarchy indicator, passing up the final evaluation result of the evaluation target in turn, and carrying out the defuzzification at the end.

3.1. Construct risk evaluation indicator system

During the construction of risk evaluation indicator system, the principles of "consistency", "measurability", "comparability", "independence" and "feasibility" shall be followed. Meanwhile, the attribute of risk factors shall be fully considered, and the risk evaluation indicator system shall be constructed according to the hierarchical structure model.

3.2. Determine factor set and evaluation set

According to the risk evaluation indicator system, the risk indicators of each hierarchy are extracted to form the factor set, and the evaluation set is the set of risk evaluation results.

3.3. Determine the weight of each risk indicator by improved AHP

In the evaluation process, the relative importance of risk indicators is called weight. AHP combines quantitative and qualitative decision-making methods, which is a common method to determine the weight. Firstly, it constructs a multi-level judgment matrix $A$ for the same hierarchy of risk indicators.

$$A = \left[ a_{ij} \right]_{n \times n} \quad (i,j=1,2,3...n) \quad (1)$$

Where: $a_{ij}$ is the importance of factor $i$ compared with factor $j$, and $a_{ij}=1/a_{ji}$, $a_{ii}=1$. Experts use the 1-9 scale method to score the importance of each risk indicator, determine the element value in the judgment matrix, then calculate the eigenvector $w$ and the maximum characteristic root $\lambda_{max}$ of the judgment matrix, and finally use the following formula:

$$CR = \frac{CI}{RI} = \frac{\lambda_{max} - n}{n - 1} \frac{1}{RI} \quad (2)$$

Where: $RI$ is the random consistency indicator, $n$ is the order of judgment matrix, $\lambda_{max}$ is the maximum eigenvalue of judgment matrix. The consistency test is carried out for judgment matrix. Only satisfying $CR < 0.1$, judgment matrix has consistency. Because there are differences in experts' understanding of concepts when using the scale measurement method, the judgment matrix often fails to pass the consistency test, and the above work needs to be repeated constantly, so it is difficult to establish the indicator weight of each hierarchy quickly and accurately. Therefore, this paper introduces the improved AHP, which creatively changes the definition of the element $a_{ij}$ in the judgment matrix from the ratio of the importance of two factors to the ratio of the weight of two indicators to constructs the judgment matrix $A'$:
W₁( i=1,2,3...n) is the weight of indicators. The eigenvalue \( \lambda'_{\text{max}} \) and eigenvector \( w' \) of the judgment matrix \( A' \) are obtained respectively, and the consistency of the judgment matrix is tested. It has been proved that the judgment matrix constructed by improved AHP has better consistency, the probability of eigenvector becoming weight vector is higher, and the adaptability and accuracy of weight vector are higher, which solves the subjective problem of expert scoring.

3.4. Determine the membership degree subset of evaluation indicator

The membership degree of evaluation indicator is to evaluate each indicator in the factor set, so as to determine the membership degree of each element in the evaluation set. Usually, the expert investigation method is used to determine the membership degree of evaluation indicator. In this paper, only the membership degree of lowest hierarchy indicator is determined to form the membership matrix.

3.5. Multi-level fuzzy comprehensive evaluation

If there are many complex risk factors in the evaluation object, the single-level fuzzy comprehensive evaluation model will find that the weight is difficult to allocate reasonably, and a large number of single information factors are buried. It is necessary to build a multi-level risk indicator system, adopt the multi-level fuzzy comprehensive evaluation model, evaluate from the risk indicator of lowest hierarchy, transfer to the upper hierarchy in turn, and obtain the final evaluation results. The three-level fuzzy comprehensive evaluation model is illustrated by taking three-level risk indicator as an example.

3.5.1. First-level fuzzy comprehensive evaluation

Construct the third-hierarchy indicator membership matrix, which is composed of the third-hierarchy indicator membership subset

\[
R_j = \begin{bmatrix}
r_{j11} & r_{j12} & r_{j13} & \cdots & r_{j1n} \\
r_{j21} & r_{j22} & r_{j23} & \cdots & r_{j2n} \\
r_{j31} & r_{j32} & r_{j33} & \cdots & r_{j3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
r_{jm1} & r_{jm2} & r_{jm3} & \cdots & r_{jmn}
\end{bmatrix}
\]  

(4)

Where: \( i \) is the indicator number of the first hierarchy, \( j \) is the indicator number of the second hierarchy, \( m \) is the indicator number of the third hierarchy, and \( n \) is the hierarchy number of evaluation set. Use the improved AHP to establish the third-hierarchy indicator weight:

\[
W_j = \begin{bmatrix}
W_{j1} & W_{j2} & W_{j3} & \cdots & W_{jm}
\end{bmatrix}
\]

(5)

Where: the meaning of number \( I, j, m \) is the same as the above. Use the multiplication rule of matrix:

\[
B_j = R_j \times w'_{ji}
\]

(6)

\( B_j \) is the result of the first-hierarchy fuzzy comprehensive evaluation and the membership degree of the second-hierarchy evaluation indicator.

3.5.2. Second-level fuzzy comprehensive evaluation

The result of the first-level fuzzy comprehensive evaluation is the basis of the second-level fuzzy
comprehensive evaluation. Similarly, the weight of the second-hierarchy indicator is determined by the improved AHP. \[ W_i = \begin{bmatrix} W_{i1} & W_{i2} & \cdots & W_{ij} \end{bmatrix} \]. The results of second-level fuzzy comprehensive evaluation are obtained by matrix multiplication method:

\[ B_i = W_i \times \begin{bmatrix} B_{i1} \\ B_{i2} \\ \vdots \\ B_{ig} \end{bmatrix} \tag{7} \]

Where: \( B_i \) is also the first hierarchy indicator membership.

3.5.3. Third-level fuzzy comprehensive evaluation

The third-level fuzzy comprehensive evaluation is the final evaluation of the model. Similarly, the results of the second-level fuzzy comprehensive evaluation should be used, and the weight of the first hierarchy indicator should be determined. The formula is as follows:

\[ B = w \times \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_g \end{bmatrix} \tag{8} \]

Where: \( W = \begin{bmatrix} W_1 & W_2 & \cdots & W_i \end{bmatrix} \) is the weight of the first-hierarchy indicator. \( B_i \) is the result of second-level fuzzy comprehensive evaluation and the first-hierarchy indicator membership. \( B \) is the result of third-level fuzzy comprehensive evaluation and the final evaluation of the model.

4. Defuzzification

Normalizing the vector \( B \), the risk level of the evaluation set corresponding to the maximum value is selected as the final evaluation result according to the maximum membership principle. However, the maximum membership method does not fully consider the impact of other indicators, and the accuracy of the final evaluation result is poor. The weighted average method can be used to obtain the final evaluation result, and the formula is:

\[ P = \frac{\sum_{j=1}^{n} b_j^k \cdot z_j}{\sum_{j=1}^{n} b_j^k} \tag{9} \]

Where: \( b_j \) is the element in vector \( B \); \( z_j \) is the element in evaluation set; \( k \) is the undetermined coefficient, taking 1 or 2 to control the influence of larger \( b_j \) on the result.

5. The application if the model

Taking the transport ships in the Yellow River Reservoir Area as an example, this paper introduces the application of multi-level fuzzy comprehensive evaluation method of improved AHP in ship safety risk evaluation.

5.1. Build the indicator system of ship risk evaluation in the reservoir area

With reference to the theory of "man-machine-environment-management" and the practice of transport ships in the Yellow River Reservoir area, the risk evaluation indicator system of transport ships in the Yellow River Reservoir area is constructed as shown in Table 1. According to the multi-level construction method, the indicator system is divided into three hierarchies, with "natural environment",

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"navigation order", "ship operation status" and "management factors" selected as the first-hierarchy indicators, "weather", "geological disaster" and "hydrology" as the second-hierarchy indicators of "natural environment", and "wind", "rain", "fog" and "temperature" as the third-hierarchy indicators of "weather", and the second-hierarchy indicators and the third-hierarchy indicators of the remaining three first-hierarchy indicators are constructed by analogy.

Table 1. Safety risk evaluation indicator system of transport ships in the Yellow River Reservoir area.

| Overall indicator | First-hierarchy indicator \((U_i)\) | Weight \((w_i)\) | Second-hierarchy indicator \((U_{ij})\) | Weight \((w_{ij})\) | Third-hierarchy indicator \((U_{ijm})\) | Weight \((w_{ijm})\) |
|-------------------|----------------------------------|----------------|----------------------------------|----------------|----------------------------------|----------------|
| Natural environment \((U_1)\) | 0.40 | Weather \((U_{11})\) | 0.40 | Wind \((U_{111})\) | 0.33 |
| Safety risk evaluation indicator system of transport ships in the Yellow River Reservoir area | 0.15 | Weather \((U_{11})\) | 0.40 | Rain \((U_{112})\) | 0.32 |
| | 0.30 | Geological disaster \((U_{12})\) | 0.30 | Fog \((U_{113})\) | 0.25 |
| | 0.30 | Hydrology \((U_{13})\) | 0.30 | Temperature \((U_{114})\) | 0.10 |
| | 0.60 | Channel patency \((U_{21})\) | 0.60 | Landslide \((U_{121})\) | 0.50 |
| | 0.33 | Ship order \((U_{22})\) | 0.40 | Mud-rock flow \((U_{122})\) | 0.50 |
| | 0.33 | Ship proximity \((U_{31})\) | 0.33 | Flow rate \((U_{131})\) | 0.30 |
| | 0.33 | Ship speed \((U_{32})\) | 0.33 | Flow regime \((U_{132})\) | 0.40 |
| | 0.34 | Ship loading \((U_{33})\) | 0.34 | Water level change \((U_{133})\) | 0.30 |
| | 0.80 | Personnel management \((U_{41})\) | 0.80 | Channel width \((U_{331})\) | 0.40 |
| | 0.20 | Ship management \((U_{42})\) | 0.20 | Channel depth \((U_{332})\) | 0.40 |
| Management factor \((U_4)\) | 0.3 | | | Bridge \((U_{333})\) | 0.20 |
| | | | | Hazardous article ship ratio \((U_{221})\) | 0.50 |
| | | | | Passenger ferry ratio \((U_{222})\) | 0.50 |
| | | | | Sailing distance \((U_{311})\) | 1.00 |
| | | | | Safe speed \((U_{321})\) | 0.60 |
| | | | | Launch speed \((U_{322})\) | 0.40 |
| | | | | Draft of ship \((U_{331})\) | 0.30 |
| | | | | Wind area of ship \((U_{332})\) | 0.30 |
| | | | | Loading properties \((U_{333})\) | 0.40 |
| | | | | Driving fatigue \((U_{411})\) | 0.75 |
| | | | | Personnel violation record \((U_{412})\) | 0.25 |
| | | | | Ship maintenance record \((U_{421})\) | 0.50 |
| | | | | Ship violation record \((U_{422})\) | 0.50 |
5.2. Determine the factor set and evaluation set of the evaluation indicator system

According to the safety risk evaluation indicator system of transport ship in the Yellow River Reservoir area constructed, the factor set is determined to be composed of four first-hierarchy indicators, ten second-hierarchy indicators and 24 third-hierarchy indicators. According to the international practice, combined with the influence degree of risk factors on ship safety, the evaluation set adopts the five-level evaluation method, \( Z = \{ \text{safe} (Z_1), \text{relatively safe} (Z_2), \text{critical} (Z_3), \text{relatively dangerous} (Z_4), \text{dangerous} (Z_5) \} = [-2, -1, 0, 1, 2] \).

5.3. Establish the membership degree subset of the lowest hierarchy indicators

The expert investigation method is used to obtain the membership degree subset of the lowest hierarchy indicators. Collect the meteorological and traffic data and other relevant data affecting the safety of transport ships in the Yellow River Reservoir area of a certain day, distribute 100 questionnaires of membership degree to professors of maritime colleges, officials of the maritime bureau, experts of shipping enterprises, captain, chief mate and chief engineer of ships in the reservoir area, and collect 96 valid questionnaires. According to the principle and method of statistics, the membership degree subset of the lowest hierarchy indicator of transport ships in the Yellow River Reservoir area is obtained as shown in Table 2 below.

Table 2. The membership degree subset of the lowest hierarchy indicator of transport ships in the Yellow River Reservoir area

| Second-hierarchy indicator (U_i) | Third-hierarchy indicator (U_{ijm}) | Collected data | Membership degree of navigation safety (R_{ijm}) |
|---------------------------------|-------------------------------------|---------------|-----------------------------------------------|
| Wind                            |                                       | below level 3 | safe 0.42, relatively safe 0.45, critical 0.13, relatively dangerous 0, dangerous 0 |
| Rain                            |                                       | more than 100mm | 0, 0, 0.12, 0.59, 0.29 |
| Visibility                      |                                       | medium        | 0, 0, 0.12, 0.82, 0.06 |
| Temperature                     |                                       | above 30°C    | 0.13, 0.11, 0.54, 0.21, 0.01 |
| Landslide                       |                                       | yes           | 0.60, 0.40, 0, 0, 0 |
| Mud-rock flow                   |                                       | yes           | 0.60, 0.40, 0, 0, 0 |
| Flow rate                       |                                       | above 1.0m/s  | 0, 0.12, 0.82, 0.06, 0 |
| Flow regime                     |                                       | complicated   | 0, 0.06, 0.53, 0.41, 0 |
| Water level change              |                                       | relatively    | 0.12, 0.59, 0.29, 0, 0 |
| Channel width                   |                                       | large         | 0.30, 0.40, 0.30, 0, 0 |
| Channel depth                   |                                       | below 3m      | 0, 0, 0.40, 0.60 |
| Obstruction                     |                                       | relatively    | 0.30, 0.40, 0.20, 0.10, 0 |
| Hazardous article ratio         |                                       | above 20%     | 0.10, 0.20, 0.30, 0.20, 0.20 |
| Passenger ferry ratio           |                                       | 20-35%        | 0.40, 0.20, 0, 0.30, 0.10 |
| Sailing distance                |                                       | above 20m     | 0.50, 0.30, 0.20, 0, 0 |
| Safe speed                      |                                       | above 50km/h  | 0, 0.20, 0.30, 0.30, 0.20 |
| Launch speed                    |                                       | above 50km/h  | 0.20, 0.30, 0.50, 0, 0 |
| Draft of ship                   |                                       | no-load       | 0.40, 0.40, 0.20, 0, 0 |
| Wind area of ship loading       |                                       | large         | 0.20, 0.30, 0.30, 0.30, 0 |
| Loading properties              |                                       | oils          | 0.20, 0.10, 0.30, 0.30, 0.10 |
5.4. Establish the weight of risk indicators at each hierarchy
When the membership questionnaire is distributed to experts, the weight questionnaire is also distributed. Make statistics and sort out the data, and establish the weight of risk indicators at each hierarchy according to the improved AHP in Section 2.3, as shown in Table 1.

5.5. Fuzzy comprehensive evaluation and defuzzification
Using the principle and method of three-level fuzzy comprehensive evaluation, combined with the weight of risk indicators at each hierarchy obtained by the improved AHP, as shown in Table 1, and the membership subset of third-hierarchy indicators, as shown in Table 2, respectively, the results of fuzzy comprehensive evaluation of the second-hierarchy indicator, fuzzy comprehensive evaluation of the first-hierarchy indicator and the final evaluation of the model are obtained, as shown in Table 3 below.

According to the maximum membership principle, it can be seen that the maximum value of 0.32 in the final evaluation result corresponds to the risk item in the evaluation set, which indicates that the ships in the reservoir area are in danger under this condition, and measures such as anchoring or berthing nearby are needed. According to the weighted average method, the final evaluation result B and evaluation set Z are weighted according to formula (9). Taking K=1, P = -0.24 is obtained. Compared with the evaluation set, it can be seen that it is close to the critical value, indicating that the crew need to strengthen the vigilance, and strive to use the existing resources to promote the ship safety in the reservoir area.
6. Conclusion
In view of the numerous and complicated risk sources, the multi-level risk evaluation indicator system is established firstly, then the weight of risk indicators at each hierarchy is established by the improved AHP method. The membership degree subset of the lowest hierarchy indicators is determined by the expert investigation method, and then the multi-level fuzzy mathematical model is used to evaluate it. Finally, the case study of the transport ships in the Yellow River Reservoir area is carried out, and the research results show that the multi-level fuzzy comprehensive evaluation model of improved AHP can solve the problem of safety evaluation of transport ships well, which proves the scientificity, rationality and accuracy of the model. However, the application of the model requires a lot of matrix calculation. If the model is programmed and the software of safety evaluation and early warning of transport ships is developed on the computer or mobile phone terminal, it can solve the problem of usability.

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References
[1] Yan,C.,Ma,L.(2011)Gray fuzzy comprehensive assessment to the risk of the oil spillage from ships in inland waterway.Ship Science and Technology,33:113-117.
[2] Fan,H.(2004)Study on the method of ship comprehensive safety assessment (FSA) .Wuhan University of Technology ,Wu Han,China,48-50.
[3] Kosee,J.(2003)Simulation of marine traffic in istanbul strait.Simulation Modelling Practice and Theory,26:597-608.
[4] Basare,J.(2010)Investigation into marine traffic and risky area in the Turkish Straits system: Canakkale Strait.Transport,25:5-10.
[5] Liu,D.,Xie,X..(2019)Evaluation of operation of LNG ships by means of AHP.Navigatio n of China,42:125-128.
[6] Su,Z.(2018)Risk prediction of ship grounding based on fuzzy comprehensive evaluation.Ship Science and Technology,40:169-171.
[7] li,Z.,Jin,Z(2009)Research on the evaluation of energy-saving emission reduction for the port and shipping system based on the AHP - fuzzy comprehensive evaluation.Ship&Ocean Engineering,38:173-176.
[8] Sun,X.,Chen,Y.,Yuan,S(2017)Fire safety assessment for the fire-prone units based on the renovated hierarchical analysis process .Journal of Safety and Environment,17:1253-1257.