The Optimize of Tug Configuration Based on Fuzzy Comprehensive Evaluation and Entropy Weight Analysis

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Abstract: As ships increasingly become larger, the corresponding port facilities can’t meet the requirements of arriving ships. This paper will use fuzzy comprehensive evaluation and analytic hierarchy process to propose an optimization plan for the configuration of port tugboats. In order to obtain the optimal tugboat configuration plan, entropy weight method is introduced in the weight analysis of the original fuzzy comprehensive evaluation to confirm the weight of evaluation factors. The problem of partial subjectivity in the determination of factor weights in the existing fuzzy synthesis method is improved. The tugboat configuration proposed at the end of this article is consistent with the existing Qingdao Port tugboat configuration mode.

1. Introduction
In port facilities, tugboats are an essential part 0. When ships enter and exit ports, they need the assistance of tugboats. The time when the ship arrives at the port is random, so the tug that each ship needs to be equipped with at the port is directly related to the ship’s captain [2].

At present, domestic and foreign scholars mainly include computer simulation research and quantitative prediction on port tugboat configuration [3]. About computer simulation research [4], a series of evaluation methods such as Particle Swarm Optimization, Fuzzy Comprehensive Evaluation, and Entropy Weight TOPSIS. This paper introduces the "Entropy Weight" method to eliminate the shortcomings of Fuzzy Comprehensive Evaluation[5], such as strong subjectivity and large errors, and establish the optimal matrix of the system to obtain the best the tugboat configuration.

2. Method introduction
2.1 Fuzzy comprehensive evaluation model
Fuzzy comprehensive evaluation is a comprehensive evaluation method based on fuzzy mathematics[6], which transforms qualitative evaluation into quantitative evaluation based on fuzzy mathematics:

1, Select evaluation factors and divide the evaluated system into m factor subsets as in equation (1):

\[ U = \{u_1, u_2, u_3, \ldots, u_m\} \]  \hspace{1cm} (1)

\( u_i \) is the i-th factor subset of factors in the system, which is determined by the n factors of the second level in the system as in equation (2):

\[ u_i = \{u_{i1}, u_{i2}, u_{i3}, \ldots, u_{in}\} \]  \hspace{1cm} (2)

2, Establish weights and construct a pairwise judgment matrix[7].

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2, Establish weights and construct a pairwise judgment matrix[7].
Table 1. Definition of importance

| Importance Scale | Importance Meaning                      |
|------------------|----------------------------------------|
| 1                | the two factors have the same importance|
| 3                | the former is slightly more important than latter|
| 5                | the former is more important than latter|
| 7                | the former is very important than latter|
| 9                | the former is extreme important than latter|

Table 2. Definition of secondary importance

| Secondary Importance Scale | Secondary Importance Meaning                      |
|----------------------------|----------------------------------------|
| 1                          | the two factors have the same importance         |
| 1/3                        | the latter is slightly more important than former|
| 1/5                        | the latter is more important than former         |
| 1/7                        | the latter is very important than former         |
| 1/9                        | the latter is extreme important than former      |

A certain numerical is used to illustrate the definition of the importance of factors as shown in Table 1 and 2 above. By judging the importance of the sub-factors, constructing a matrix as in equation (3):

\[
\begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1n} \\
    r_{21} & r_{22} & \cdots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nn}
\end{bmatrix}
\]

(3)

The above pairwise judgment matrix has the follow properties[8]:

1. All factors in the judgment matrix are greater than zero;
2. The factor of the main diagonal is one;
3. The diagonally symmetric factors in the judgment matrix are the reciprocal of each other.

Calculating the maximum eigenvalue and eigenvector for the above judgment matrix. In order to make the evaluation conclusions more reliable, the consistency index \( CI \) is introduced as in equation (4):

\[
CI = \frac{R_{\text{max}} - n}{n - 1}
\]

(4)

When the matrix is consistent, it should have \( R_{\text{max}} = n \), the conclusion is accurate. When the matrix isn’t consistent, divide the consistency index calculated by the formula of the random consistency index, it means \( CI/CR < 0.1 \), the conclusion is valid, the random consistency index is shown in Table 3 below:

Table 3. Average random consistency index

| N (indicators numbers) | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
|------------------------|----|----|----|----|----|----|----|----|----|
| CR                     | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 | 1.49 | 1.52 |

3. After verification, the consistency of the above judgment matrix meets the requirements, and its eigenvector \( A_i \) as in equation(5):

\[
A_i = [a_{i1}, a_{i2}, a_{i3}, \ldots, a_{im}]
\]

(5)

The judgment matrix \( A \) composed of eigenvectors \( A_i \) is multiplied by the eigenvector \( r_i \) of the judgment matrix [9], the system evaluation index as in equation (6):

\[
B = A \times r = \begin{bmatrix}
    a_{11} & a_{12} & \cdots & a_{1m} \\
    a_{21} & a_{22} & \cdots & a_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{n1} & a_{n2} & \cdots & a_{nm}
\end{bmatrix} \cdot \begin{bmatrix}
    r_{i1} \\
    r_{i2} \\
    \vdots \\
    r_{in}
\end{bmatrix}
\]

(6)
2.2 "Entropy Weight" Fuzzy Comprehensive Evaluation Model

Entropy can measure the effectiveness of information in the system. When the entropy value of the evaluation object is small, it means that effective information is large. Therefore, the Entropy Weight is an objective method, which can effectively solve the strong subjectivity in AHP, it includes three steps:

1. The data matrix which there are m evaluation indicators and n evaluation objects as in equation (7):

\[
X = \begin{pmatrix}
X_{11} & X_{12} & \cdots & X_{1n} \\
X_{21} & X_{22} & \cdots & X_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
X_{m1} & X_{m2} & \cdots & X_{mn}
\end{pmatrix}
\]

In the above matrix, \(R_{ij}\) is the standard value of the j-th evaluation object on the i-th evaluation index. The value of \(R_{ij}\) for the profitability index that is better for the larger as in equation (8) [10]:

\[
R_{ij} = \frac{x_{ij} - \min \{x_{ij}\}}{\max \{x_{ij}\} - \min \{x_{ij}\}}
\]

The value of \(R_{ij}\) for the profitability index that is better for the smaller as in equation (9):

\[
R_{ij} = \frac{\max \{x_{ij}\} - x_{ij}}{\max \{x_{ij}\} - \min \{x_{ij}\}}
\]

2. Defining entropy, the entropy of the i-th index is defined as in equation (10):

\[
H_i = -k \sum_{j=1}^{n} f_{ij} \ln f_{ij}
\]

Above illustrated, \(f_{ij} = R_{ij} / \sum_{i=1}^{n} R_{ij} \), \(k = 1 / \ln n \), when \(f_{ij} = 0 \), then \(f_{ij} \ln f_{ij} = 0 \).

3. The Entropy Weight calculation formula of the i-th index as in equation (11):

\[
w_i = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i}
\]

In the matrix, \(0 < w_i < 1 \), \(\sum_{i=1}^{m} W_i = 1 \).

2.3 Combination Weighting Calculation

Use the AHP and Entropy Weight assignment to optimize the tugboat configuration model[11], the calculation method as in equation (12):

\[
w_j = \frac{u_j v_j}{\sum_{j=1}^{n} u_j v_j}
\]

Among above, \(w_j\) is the mixed weight, \(u_j\) is the weight obtained by the AHP, \(v_j\) is the weight obtained by the Entropy Weight method, and the flow chart is shown in ‘Figure 1’:

---

Figure 1: Flow chart of entropy weight fuzzy comprehensive evaluation model.
3. Examples

3.1 Qingdao Port existing tugboats equipment

The ships of different types, captains and ship drafts which required tugboats are not the same. Taking Qingdao Port as an example, the number and power of tugboats in Qingdao Port are shown in Table 4:

| Servicing Port   | Power/hp | Tugboat name       | Remark                                      |
|------------------|----------|--------------------|---------------------------------------------|
| Qingdao Port     | 3200     | Qing tow 3, Qing tow 5, Qing tow 15 | -                                           |
|                  | 4000     | Qing tow 18, Qing tow 20, Qing tow 21, Qing tow 22, Qing tow 23, Qing tow 25, Qing tow 26, Qing tow 29 | -                                           |
|                  | 5000     | Asian 1, Asian 2, Asian 3, Asian 6, Asian 7, Asian 9, Asian 10, Asian 11, Asian 12, Asian 17, Asian 18, Qing tow 6, Qing tow 9, Qing tow 12, Qing tow 27 | -                                           |
| Dongjiakou Port  | 7000     | Qing tow 2         | -                                           |
|                  | 8000     | Huan6th            | -                                           |
|                  | 2600     | Qing port          | -                                           |
|                  | 4000     | Qing tow 28, Qiang port | -                                           |
|                  | 5000     | Huan tow 1, Qing tow 8, Qing tow 16, Asian 15, Asian 16 | -                                           |
|                  | 7000     | Huan tow 2, Huan1th, Huan2th | -                                           |
|                  | 8000     | Huan3th            | -                                           |
|                  | 4000     | Fu port            | -                                           |
|                  | 3200     | Qing tow 14        | -                                           |

Qingdao Port's current tugboat usage method is shown in Table 5 below:

| Ship's type                  | Captain /m | Ship draft/m | Tugboat power /hp | Remark                                      |
|------------------------------|-------------|--------------|-------------------|---------------------------------------------|
| Tanker                       | L>265       | D>18         | 30000±10%         | Oil tankers with a draft less than 14m do not use 7000 horsepower tugs. |
|                              | 15<D<18     | D=15         | 22000±10%         |                                             |
|                              | D=15        | 18000-15000  |                   |                                             |
|                              | D=13        | 20000±10%    |                   |                                             |
|                              | D<13        | 15000±10%    |                   |                                             |
|                              | D=12        | 11000±10%    |                   |                                             |
|                              | D<12        | 18000±10%    |                   |                                             |
|                              | 180<L<235   | D=12         | 10000±10%         |                                             |
|                              | D=9         | 8400—7200    |                   |                                             |
|                              | D=9         | 6400—5550    |                   |                                             |
| General cargo ship           | 100<L<130   | -            | 9000±10%          | General cargo ships with draft less than 17.5 do not use 7000 tugs. |
|                              | L<100       | -            | 6400±10%          |                                             |
|                              | L>390       | -            |                   |                                             |
| Container                    | 260<L<390   | -            | Berthing 3 tugboats above 5000 power, leaving two tugboats above 5000 power | 5000-horsepower tugboats are not used for containers less than 200 in length. |
|                              | 200<L<260   | -            | Assisted by 2 5000-power tug boats |                                             |
|                              | 260<L<320   | D=18         | 9000±10%          |                                             |
|                              | D=18        | 25000±10%    |                   |                                             |
|                              | D>18        | 21000±10%    |                   |                                             |
|                              | 260<L<320   | D=13         | 21000±10%         |                                             |
|                              | 16<D<18     | 18000±10%    |                   |                                             |
|                              | D=12        | 15000±10%    |                   |                                             |
|                              | 12.5<L      | 10000±10%    |                   | Bulk-class oil tankers under 200 captains do not use 5,000 horsepower tugs. |
| Bulk carrier                 | 220<L<240   | 10<L<12.5    | 9000±10%          |                                             |
3.2 Comprehensive evaluation model establishment

In view of the Qingdao Port tugboat equipment and usage, the tug configuration will be based on economic benefits, social benefits, port environmental, and tugboats themselves in 4 aspects to optimize.

1. Economic benefits: The tugboat from the purchased to the port using, crew salary, ship’s depreciation, fuel cost, etc are all we need to consider

2. Social benefits: Social benefits include tugboat utilization, port utilization, tugboat service time, and average ship waiting time [12]. The above factors can reflect the efficiency of the tugboats system.

3. Port environmental factors: The average annual wind speed is 5.5m/s, the average sea level is 2.45m; the average high tide level is 3.85m; the average low tide level is 1.1m; the maximum tidal velocity it can reach 3.0m/s.

4. Tugboats itself: The cargo throughput of Qingdao Port in 2019 was 515 million tons. In the 《Master Plan for Qingdao Port (2018-2035)》, it predicted that the cargo throughput will reach 670 million tons by 2025. According to port cargo throughput, the increase of 155 million tons in 2025 should be supplemented with a total of 35,000 HP tugs.

At present, most of the tugboats in Qingdao Port are mainly 4000 and 5000 horsepower. Therefore, it is recommended that Qingdao Port supply 7 tugboats. The plan is as follows:

(1) 1 tug with 3000 horsepower, 4 tugs with 4000-5000 horsepower, 2 tugs with 7000 horsepower
(2) 2 tug with 3000 horsepower, 4 tugs with 4000-5000 horsepower, 1 tug with 7000 horsepower
(3) 1 tug with 3000 horsepower, 5 tugs with 4000-5000 horsepower, 1 tug with 7000 horsepower

Next, the evaluation system is shown in Table 6:

| R1 economic factors | R11 Purchase cost | R12 Ship depreciation | R13 Ship maintenance | R14 Crew salary | R15 Fuel costs |
|---------------------|-------------------|-----------------------|----------------------|----------------|---------------|
| R2 environmental factors | R21 Wind | R22 Wave | R23 Flow | R24 Water depth |
| R3 tugboat itself | R31 Wind resistance rating | R32 Power | R33 Speed | R34 Captain |
| R4 social benefits | R41 Port utilization | R42 Tugboat utilization | R43 Average service time of tugboat | R44 Average ship waiting time |

3.3 Model calculation

According to the first configuration plan, the two matrixes are constructed for economic factors through survey interviews and expert consultation methods. The results are as follows:

\[
R = \begin{bmatrix}
1 & 1 & 3.3 & 2.67 & 4 & 8 \\
0.75 & 1 & 2 & 3 & 6 \\
0.375 & 0.5 & 1 & 1.5 & 3 \\
0.25 & 0.33 & 0.67 & 1 & 2 \\
0.125 & 0.17 & 0.33 & 0.5 & 1
\end{bmatrix}
\]

\[
R^* = \begin{bmatrix}
0 & 0 & 0 & 0 & 0.43 \\
1 & 1 & 0.82 & 1 & 0.05 \\
0.66 & 0.47 & 0.41 & 0.43 & 0 \\
0.78 & 0.87 & 1 & 0.24 & 1 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

Analytic hierarchy process

Entropy matrix

Bring the above two matrices into the matlab program to get the analytic hierarchy process weight \(w_1=[0.4, 0.3, 0.15, 0.1, 0.05]\), its maximum characteristic value is 5.007, it meets Consistency verification requirements, Entropy Discriminant Matrix Weight \(w_1=[0.217, 0.205, 0.202, 0.162, 0.206]\), calculated by combination weighting formula \(w_1=[0.424, 0.3, 0.146, 0.08, 0.05]\).
The analytic for the environmental factors:

\[
R_3 = \begin{bmatrix}
1 & 1.17 & 1.4 & 3.5 \\
0.86 & 1 & 1.2 & 3 \\
0.71 & 0.83 & 1 & 2.5 \\
0.29 & 0.33 & 0.4 & 1 \\
\end{bmatrix}
\]

\[
R_2 = \begin{bmatrix}
0.33 & 0.7 & 0 & 0 \\
1 & 1 & 1 & 1 \\
0.56 & 0.9 & 0.5 & 0.5 \\
0 & 0 & 0.5 & 0 \\
\end{bmatrix}
\]

Analytic hierarchy process

Entropy matrix

The analytic hierarchy process weight \( w_2 = [0.35, 0.3, 0.25, 0.1] \), its maximum characteristic value is 4.003, it meets Consistency verification requirements, Entropy Discriminant Matrix Weight \( w_2 = [0.21, 0.3, 0.2, 0.29] \), calculated by combination weighting formula \( w_2 = [0.3, 0.37, 0.21, 0.12] \).

The analytic for the tugboat itself:

\[
R_1 = \begin{bmatrix}
1 & 1.14 & 2.67 & 4 \\
0.875 & 1 & 2.33 & 3.5 \\
0.375 & 0.43 & 1 & 1.5 \\
0.25 & 0.29 & 0.67 & 1 \\
\end{bmatrix}
\]

\[
R_1 = \begin{bmatrix}
0.77 & 0.56 & 1 & 0.4 \\
0.49 & 0.23 & 0 & 0 \\
0 & 0 & 0.77 & 1 \\
1 & 1 & 0.41 & 0.08 \\
\end{bmatrix}
\]

Analytic hierarchy process

Entropy matrix

The analytic hierarchy process weight \( w_3 = [0.39, 0.35, 0.16, 0.1] \), its maximum characteristic value is 4.005, it meets Consistency verification requirements, Entropy Discriminant Matrix Weight \( w_3 = [0.26, 0.23, 0.26, 0.25] \), calculated by combination weighting formula \( w_3 = [0.41, 0.32, 0.17, 0.1] \).

The analytic for the social benefits:

\[
R_4 = \begin{bmatrix}
1 & 1.17 & 1.75 & 2.33 \\
0.86 & 1 & 1.5 & 2 \\
0.57 & 0.67 & 1 & 1.33 \\
0.43 & 0.5 & 0.75 & 1 \\
\end{bmatrix}
\]

\[
R_4 = \begin{bmatrix}
1 & 0 & 0.43 & 0.31 \\
0 & 0.4 & 0.68 & 0.2 \\
0.92 & 1 & 0 & 0 \\
0.42 & 0.31 & 1 & 1 \\
\end{bmatrix}
\]

Analytic hierarchy process

Entropy matrix

The analytic hierarchy process weight \( w_4 = [0.35, 0.31, 0.19, 0.15] \), its maximum characteristic value is 4.002, it meets Consistency verification requirements, Entropy Discriminant Matrix Weight \( w_4 = [0.31, 0.21, 0.25, 0.23] \), calculated by combination weighting formula \( w_4 = [0.42, 0.25, 0.19, 0.14] \).

Configuration scheme two:

The Analytic Hierarchy process shows that the weight has not changed much compared with the scheme one. The Entropy Weight assignment discriminant matrix is discussed in detail below:

\[
R_1 = \begin{bmatrix}
0 & 0 & 0.6 & 0.92 \\
1 & 0.67 & 0.38 & 0.8 \\
0.82 & 0.58 & 0.25 & 1 \, 0.14 \\
0.86 & 1 & 1 & 0 \, 1 \\
\end{bmatrix}
\]

\[
R_1 = \begin{bmatrix}
0.67 & 0.61 & 0.27 & 0 \\
0.44 & 0.15 & 0 & 1 \\
0 & 1 & 1 & 0.83 \\
1 & 0 & 0.63 & 0.33 \\
\end{bmatrix}
\]

Economic

Environmental

\[
R_2 = \begin{bmatrix}
0.71 & 0.54 & 1 & 0 \\
0.82 & 0.55 & 0 & 0.67 \\
0 & 0 & 0.5 & 0.33 \\
1 & 1 & 0.83 & 1 \\
\end{bmatrix}
\]

\[
R_2 = \begin{bmatrix}
1 & 0 & 0.67 & 0.43 \\
0 & 0.5 & 0.5 & 0 \\
0.69 & 1 & 0 & 0.36 \\
0.25 & 0.33 & 1 & 1 \\
\end{bmatrix}
\]

Tow

Social

After calculating, theirs Entropy Weights are \( w_1 = [0.24, 0.18, 0.15, 0.2, 0.23] \), \( w_2 = [0.24, 0.25, 0.23, 0.28] \), \( w_3 = [0.29, 0.22, 0.26, 0.23] \), \( w_4 = [0.27, 0.23, 0.26, 0.24] \), calculated by combination weighting formula are as follow:

\[
w_1 = [0.47, 0.26, 0.11, 0.09, 0.07] , \ w_2 = [0.34, 0.31, 0.23, 0.12] \\
w_3 = [0.34, 0.23, 0.36, 0.07] , \ w_4 = [0.38, 0.28, 0.2, 0.14] \\
\]

Configuration scheme three:

\[
R_1 = \begin{bmatrix}
0 & 0.07 & 0 & 0.78 & 1 \\
0.69 & 0.5 & 0.29 & 0.12 \\
0.48 & 0 & 0.2 & 0 & 0 \\
\end{bmatrix}
\]

\[
R_1 = \begin{bmatrix}
0.44 & 0.6 & 0.1 & 0.17 \\
0.56 & 1 & 0 & 0.28 \\
0 & 0 & 0.4 & 0 \\
\end{bmatrix}
\]

Economic

Environmental
After calculating, theirs Entropy Weights are \( w_{t1} = [0.19, 0.21, 0.21, 0.2, 0.19] \), \( w_{t2} = [0.22, 0.31, 0.24, 0.23] \), \( w_{t3} = [0.25, 0.29, 0.23, 0.23] \), \( w_{t4} = [0.29, 0.24, 0.22, 0.24] \), calculated by combination weighting formula are as follow:

\[
\begin{align*}
R &= \begin{bmatrix}
0.67 & 0.32 & 0.2 & 0.54 \\
0.33 & 0 & 0 & 0 \\
0 & 0.05 & 0.45 & 0.23 \\
1 & 1 & 1 & 1
\end{bmatrix} \\
R &= \begin{bmatrix}
1 & 0.18 & 0.6 & 0.1 \\
0 & 0 & 1 & 0 \\
0.71 & 0.64 & 0 & 1 \\
0.76 & 1 & 0.4 & 0.2
\end{bmatrix}
\end{align*}
\]

Then constructing a judgment matrix for the first-level indicators of the tugboat evaluation system:

\[
R = \begin{bmatrix}
1 & 1.6 & 2 & 2.67 \\
0.63 & 1 & 1.25 & 1.67 \\
0.5 & 0.8 & 1 & 1.33 \\
0.38 & 0.6 & 0.75 & 1
\end{bmatrix}
\]

After calculating, the Weights is \( w = [0.39, 0.26, 0.12, 0.15] \), its maximum characteristic value is 4.005, it meets Consistency verification requirements.

4. Conclusion

The eigenvectors obtained from the configuration schemes form matrix A, and the overall evaluation index of the system is obtained through the formula \( B = A \cdot w \). Among them, the overall evaluation index of the tugboat configuration scheme one is 0.908, the second scheme is 0.894, the third scheme is 0.922.

Summary, in order to better respond to the development situation of the Qingdao Port, but there are still problems such as insufficient evaluation indicators and incomplete evaluation factors. The evaluation of the entire tugboat operating system needs further study.

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