Research and Countermeasures on LNG Ship Port Area Navigation Risk Assessment Based on Fuzzy Comprehensive Evaluation Method

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Abstract. As a new energy source, LNG occupies an important position in the energy structure, and it is of great significance to carry out research on the navigation risks of LNG ships as carriers. Through the establishment of an LNG ship port area risk evaluation index system, the a² exponential scale method in the analytic hierarchy process is used to calculate the weight value of each index, and the fuzzy comprehensive evaluation method is used to calculate the navigation risk level of LNG ships. An LNG ship in Lusi port area of Nantong Port is selected for risk assessment, and based on the results of the risk evaluation, a targeted risk control plan is proposed.

1. Introduction

With the "One Belt, One Road" and "Yangtze River Economic Belt" proposed, shipping on the Yangtze River has shown a rapid development trend in recent years. The navigation density of waters such as ports and waterways has greatly increased, and the traffic environment has become more complicated. The rapid development of LNG port area transportation and the busy operation of LNG ships in the port have a greater impact on the navigation environment of the LNG terminal port water area and ship navigation safety, and also put forward new requirements for port management and maritime management. How to identify the navigation risks of LNG ship ports and take targeted measures to reduce the probability of LNG ship traffic accidents and possible losses caused by accidents is of great significance for ensuring the navigation safety of LNG ship ports and improving the navigation environment.

At present, domestic and foreign researchers have used relevant theoretical knowledge, using the method of combining theory and practice to study the safe navigation of LNG ships [1]; Qi Chaozhong started from the characteristics of LNG and discussed the hazardous characteristics of LNG ship operations in the port and preventive measures [2]; Niu Dongxiang uses the analytic hierarchy process to establish an LNG ship evaluation model, and conducts risk evaluation on the process of LNG ship loading and unloading from the perspective of LNG receiving stations [3]. NWAHOA uses the risk matrix method to identify the main hazards of LNG ships during transportation, and the results show that the two events of LNG overflow and control system failure of loading arms have the highest hazard levels [4]. Fuzzy comprehensive evaluation method is a prediction and evaluation method based on fuzzy mathematics theory, which can better solve fuzzy and difficult to quantify problems [5]. At present, the research on the LNG ship ports navigation risk does not fully identify potential risk sources and risk factors, and the quantitative analysis is not comprehensive. In this regard, this article uses the method
of fuzzy comprehensive evaluation, combined with the analytic hierarchy process, to construct the LNG ship port navigation risk assessment model for systematic research.

2. Construction of LNG ship port area navigation risk assessment model

2.1 Navigation risk evaluation index system for LNG ship port area

According to relevant research results [5,6,7] and expert opinion consultation, it is established that LNG ship port area navigation risk factors include four types of first-level risk factors, such as environmental factors, ship factors, human factors, management factors. Each first-level risk factor includes several secondary risk factors. In this way, an LNG ship port area navigation risk evaluation index system is established, as shown in Table 1. The established factor set U contains 4 sub-categories and 15 evaluation indicators.

| Primary factor | Secondary factors                        |
|----------------|------------------------------------------|
| Environmental factor (U₁) | Wind force (U₁₁) |
|                     | Flow rate (U₁₂)                          |
|                     | visibility (U₁₃)                          |
|                     | Water depth (U₁₄)                         |
|                     | Channel curvature (U₁₅)                    |
|                     | Traffic volume (U₁₆)                      |
|                     | Ship age (U₁₇)                            |
| Ship factors (U₂) | Ship structural strength (U₂₂)            |
|                     | Ship size (U₂₃)                           |
|                     | Compliance with laws and regulations (U₃₁) |
| Human factors (U₃) | Crew qualification (U₃₂)                   |
|                     | Crew and pilot safety awareness (U₃₃)      |
|                     | Crew and pilot skill levels (U₃₄)          |
| Management factors (U₄) | Maritime department management level (U₄₁) |
|                     | Shipping company management level (U₄₂)    |

2.2 Analytic hierarchy process to determine index weight

2.2.1 Construct a judgment matrix

Constructing a judgment matrix is a key step of the fuzzy comprehensive evaluation method. For n elements that need to be compared, a pairwise comparison judgment matrix can be used as \( C = (c_{ij})_{n \times m} \). The method of constructing judgment matrix is 1-9 scale method, \( a^n \) (\( a^n=9 \)) exponential scaling and fractional scaling. According to related research results [8,9], \( a^n \) exponential scaling satisfactory consistency test ratio has the highest proportion of consistency test ratios of other scales. It shows that the \( a^n \) exponential scaling is more reasonable than other scales, So \( a^n \) exponential scaling is adopted to determine the judgment matrix according to the relative importance of each index \( U_i \).

2.2.2 Consistency check

The judgment matrix \( C_{ij} \) is determined according to the relative importance of the indicators recognized by experts, and it is subjective. Therefore, a consistency test is introduced to test the reliability of the judgment matrix.

\[
CR = CI / RI = \frac{\lambda_{max} - n}{n-1} / RI
\]  

(1)
In formula (1): \( CR \) is the random consistency ratio; \( RI \) is the average consistency index of \( n \) exponential type. According to related research results [9], the value of \( RI \) is shown in Table 2; \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix; \( n \) is the order of the judgment matrix. If \( CR < 0.10 \) in the formula (1), it shows that the judgment matrix has satisfactory consistency. The ratio of each element in the eigenvector corresponding to its maximum eigenvalue \( [W_1, W_2, ..., W_n]^T \) to the sum of each element is the weight value of each evaluation index; If \( CR > 0.10 \), the judgment matrix is considered unreliable, and the judgment matrix needs to be re-adjusted.

### Table 2. \( n \)th Index of average consistency on an exponential scale.

| \( n \) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( RI \) | 0   | 0   | 0.3002 | 0.4969 | 0.6219 | 0.7067 | 0.7613 | 0.8016 | 0.8351 |

### 2.3 Determine the index evaluation system

According to related research [7], the evaluation criteria of risk factors are divided into 5 levels, namely low risk, lower risk, general risk, higher risk and high risk. Comment set: \( V = \{V_1, V_2, V_3, V_4, V_5\} = \{-2,-1,0,1,2\} \) \( ("-2,-1,0,1,2" \) are fuzzy numbers \)

According to relevant research results [7,10,11], as well as interviews and consultations with experts, using fuzzy evaluation methods, the risk evaluation standards are shown in Table 3.

### Table 3. General Aviation Risk Evaluation Index Evaluation Standard

| Risk level | Lower | Low | General | High | Higher |
|------------|-------|-----|---------|------|--------|
| Wind/(level) | 0~1   | 2~3 | 4~5     | 6~7  | >8     |
| Flow rate/(m/s-1) | <0.4 | 0.4~1.2 | 1.2~2.2 | 2.2~3.2 | >3.2 |
| Days with poor visibility/(days) | 0~10 | 10~25 | 25~40 | 40~60 | >60 |
| Water depth (the ratio of ship's rich water depth to ship's draught %) | >15 | 12~15 | 10~12 | 8~10 | <8 |
| Channel curvature (°) | <20 | 20~45 | 45~60 | 60~70 | >70 |
| Traffic volume (Number of ships/day) | 0~20 | 20~40 | 40~60 | 60~80 | >80 |
| Ship structural strength | Very good | Better | Normal | Low | Very low |
| Ship age (years) | 0~5 | 5~10 | 10~15 | 15~20 | >20 |
| Ship size (m) | <160 | 160~200 | 200~230 | 230~260 | >260 |
| Crew qualification | Very good | Better | Normal | Low | Very low |
| Crew and pilot safety awareness | Very good | Better | Normal | Low | Very low |
| Crew and pilot skill levels | Very good | Better | Normal | Low | Very low |
| Compliance with laws and regulations | Very good | Better | Normal | Low | Very low |
| Maritime department management level | Very good | Better | Normal | Low | Very low |
| Shipping company management level | Very good | Better | Normal | Low | Very low |

### 2.4 Determine the membership degree of the evaluation index

The determination of membership degree is a key step of the fuzzy comprehensive evaluation method. Index factors and risk levels are fuzzy concepts, and the boundaries between adjacent levels are not obvious. Therefore, an index factor should not be described as a certain level. Each factor is vaguely distributed between the two adjacent levels [12]. For the index factors obtained by observable measurement (such as wind, velocity, visibility, water depth, channel curvature, ship size, traffic volume, and ship age), fuzzy mathematics theory can be used to construct a single-index membership function with reference to literature [7] to determine the degree of membership; for index factors that are difficult to quantify, a fuzzy subset table of the evaluation index membership degree can be constructed to determine the degree of membership [12], as shown in Table 4.
### Table 4. Fuzzy subset table of membership degree of evaluation index

| Comment rating | -2 | -1 | 0  | 1  | 2  |
|----------------|----|----|----|----|----|
| Lower risk     | 0.70 | 0.30 | 0  | 0  | 0  |
| Low risk       | 0.25 | 0.50 | 0.25 | 0  | 0  |
| General risk   | 0   | 0.25 | 0.50 | 0.25 | 0  |
| High risk      | 0   | 0   | 0.25 | 0.50 | 0.25 |
| Higher risk    | 0   | 0   | 0   | 0.30 | 0.70 |

### 3. Case Analysis

#### 3.1 Brief introduction of example LNG ships in Lusi port area

The wind force of the entry channel in the Lusi operation area of Nantong Port is level 4; the flow velocity is 0.8m/s; days with poor visibility is 24; the shallowest part of the channel is 11.2m; the channel has a maximum curvature of 13.5°, and the traffic volume is 39 ships per day. A 40,000m³ LNG ship is selected as the research object, with a total length of 204m, a width of 30m, a full-load draft of 9m, and a ship age of 6 years.

#### 3.2 Determine the weight value

According to the advice of industry experts, compare the importance of the two indicators and use the analytic hierarchy process to process the data of environmental factors, ship factors, human factors, and management factor, getting a layer of matrix A.

\[
A = \begin{pmatrix}
1 & a^1 & a^2 & a^4 \\
1 & a^{-1} & 1 & a^{-1} \\
a^3 & a^2 & 1 & a^1 \\
a^{-1} & a^1 & a^{-1} & 1
\end{pmatrix}
\]  

(2)

Calculated matrix \( A \): \( \lambda_{\text{max}} = 4.0284 \), \( RI = 0.4969 \), \( CI = 0.0284 \). Random consensus ratio \( CR = 0.019 < 0.1 \). The calculated weight value \( W = (0.2444, 0.1840, 0.3440, 0.2276) \).

In the same way, the weight value \( W_i \) of the two-layer matrix of factors such as wind, flow velocity, visibility, water depth, channel curvature, and ship traffic volume among environmental factors: \( W_i = (0.1847, 0.2431, 0.1404, 0.1847, 0.1067, 0.1404) \).

The weight value of the two-layer matrix of ship age, ship structure strength, and ship size factors among ship factors: \( W_s = (0.2211, 0.4600, 0.3189) \).

The weight value of the two-layer matrix of human factors such as compliance with laws and regulations, crew qualifications, safety awareness of pilots, and skill level of pilots: \( W_h = (0.2123, 0.1850, 0.3424, 0.2603) \).

The weight value of the two-layer matrix of management factors such as level of the maritime department and the management level of the shipping company: \( W_m = (0.3660, 0.6340) \).

According to references [7,12], the membership function can be used to calculate the degree of membership for the measurable factors; for the factors that are difficult to quantify, the evaluation method in the fuzzy subset table of the evaluation index membership degree (Table 4) is used to express the degree of membership. According to the main parameters of LNG ships and the navigation environment data of Lusi Port, combined with the opinions of industry experts, the weights and membership degrees of each evaluation index are shown in Table 5.


### Table 5. Weights and membership degrees of each evaluation index

| First-level evaluation factors | Second-level evaluation factors | Membership |
|--------------------------------|---------------------------------|------------|
| Factor                        | Item                            | Weights    | -2 | -1 | 0 | 1 | 2 |
| Environmental factor          | Wind force                      | 0.1847     | 0  | 0.250 | 0.750 | 0 | 0 |
|                               | Flow rate                       | 0.2431     | 0  | 0.700 | 0.300 | 0 | 0 |
|                               | visibility                      | 0.1404     | 0  | 0.567 | 0.433 | 0 | 0 |
|                               | Water depth                     | 0.1847     | 1.000 | 0 | 0 | 0 | 0 |
|                               | Channel curvature               | 0.1067     | 1.000 | 0 | 0 | 0 | 0 |
|                               | Traffic volume                  | 0.1404     | 0 | 0.550 | 0.450 | 0 | 0 |
| Ship factors                  | Ship age                        | 0.2211     | 0.300 | 0.700 | 0 | 0 | 0 |
|                               | Ship structural strength        | 0.4600     | 0.250 | 0.500 | 0.250 | 0 | 0 |
|                               | Ship size                       | 0.3189     | 0 | 0.366 | 0.634 | 0 | 0 |
| Human factors                 | Compliance with laws and regulations | 0.2123 | 0.250 | 0.500 | 0.250 | 0 | 0 |
|                               | Crew qualification              | 0.1850     | 0.700 | 0.300 | 0 | 0 | 0 |
|                               | Crew and pilot safety awareness | 0.3424     | 0 | 0.250 | 0.500 | 0.250 | 0 |
|                               | Crew and pilot skill levels      | 0.2603     | 0.250 | 0.500 | 0.250 | 0 | 0 |
| Management factors            | Shipping company management level | 0.3660 | 0 | 0.250 | 0.500 | 0.250 | 0 |
|                               | Maritime department management level | 0.6340 | 0.700 | 0.300 | 0 | 0 | 0 |

#### 3.3 Fuzzy comprehensive evaluation

##### 3.3.1 Fuzzy calculation

It can be seen from Table 5, fuzzy evaluation matrix of environmental factors

\[
R_i = \begin{bmatrix}
0 & 0.250 & 0.750 & 0 & 0 \\
0 & 0.700 & 0.300 & 0 & 0 \\
0 & 0.567 & 0.433 & 0 & 0 \\
1.000 & 0 & 0 & 0 & 0 \\
1.000 & 0 & 0 & 0 & 0 \\
0 & 0.550 & 0.450 & 0 & 0 
\end{bmatrix}
\]  \quad (3)

Environmental factor weight set \( W_i = (0.1847,0.2431,0.1404,0.1847,0.1067,0.1404) \). Fuzzy membership degree vector of environmental factors: \( B_i = W_i \cdot R_i = (0.2914,0.3732,0.3354,0,0) \).

Similarly, Ship factor membership vector \( B_2 \), Human factor membership vector \( B_3 \), Management factor membership vector \( B_4 \).

\( B_2 = W_2 \cdot R_i = (0.1813,0.5015,0.3172,0,0) \); \( B_3 = W_3 \cdot R_i = (0.2477,0.3773,0.2894,0.0856,0) \);
\[ B_t = W_t / R_t = (0.4438, 0.2817, 0.1830, 0.0915, 0) \] ;

Combining the above fuzzy membership degree vectors, the fuzzy comprehensive evaluation matrix of navigation risk of LNG ships in Lusi port area can be obtained.

\[
R = \begin{bmatrix}
0.2914 & 0.3732 & 0.3354 & 0 & 0 \\
0.1813 & 0.5015 & 0.3172 & 0 & 0 \\
0.2477 & 0.3773 & 0.2894 & 0.0856 & 0 \\
0.4438 & 0.2817 & 0.1830 & 0.0915 & 0
\end{bmatrix}
\]  \( (4) \)

The fuzzy comprehensive membership degree vector of LNG ship navigation risk in Lusi port area.

\[ B = W \cdot R = (0.2908, 0.3774, 0.2815, 0.0503, 0) \]  \( (5) \)

3.3.2 Anti-obfuscation

According to the weighted average method, fuzzy vector \( B \) and Comment set \( V = \{ -2, -1, 0, 1, 2 \} \) are performing weighted average processing, the result \( A \) : 

\[
A = \frac{\sum_{j=1}^{5} b_{ij} v_j}{\sum_{j=1}^{5} b_{ij}} = B \cdot V^T = -0.9087
\]

The final result of the fuzzy evaluation of the LNG ships in Lusi port area navigation risk is -0.9087. According to evaluation criteria, The LNG ships in Lusi port area navigation risk is between "low risk" and "general risk", which is closer to "low risk". There are high standards in terms of management, service, operation. Port rules and regulations are well managed in Lusi Port Area, and relevant management departments are well supervised. Therefore, the navigation risk of LNG ships in the Lusi port area is "low risk".

Similarly, the evaluation results of environmental factors, ship factors, human factors, and management factors can be obtained as \( A_1 = -0.9560 \), \( A_2 = -0.8641 \), \( A_3 = -0.7871 \), \( A_4 = -1.0778 \). Management factors are between "lower risk" and "low risk", indicating that management factors have little influence on the navigation risk of LNG ships in the Lusi port area. Environmental factors, human factors, and ship factors are between "low risk" and "general risk", and have a greater impact on the overall risk.

4. Risk control plan for LNG ship navigation in Lusi port area

According to the analysis, the risks of environmental factors, ship factors, and human factors are relatively high, and have a greater impact on the overall risk. Based on the actual situation of the Lusi Port Area and the opinions of experts, four LNG navigation risks control plan in the Lusi Port Area are proposed.

(1) Formulate corresponding LNG ship navigation standards

Establish corresponding LNG ship navigation standards, pay attention to meteorological and hydrological information, and avoid navigating under conditions that affect navigation safety such as strong winds, rapids, heavy fog, and cold waves. It is recommended that LNG ships enter and leave the channel under the conditions of wind \( \leq 6 \) knots, flow velocity \( \leq 4 \) knots, and visibility should generally not be less than 2000m.
(2) Formulate emergency plans
It is necessary to formulate initial emergency plans for leakage, fire, explosion, collision, stranding, etc. Train terminal management personnel, and actively absorb advanced management concepts and systems based on the operating experience of international LNG terminals.

(3) Enhance the inspection of navigable LNG ships in the port area
The law enforcement agencies of the Maritime Safety Administration need to increase inspections of ships, detain ships that are unseaworthy, strictly control "three noes" ships, and improve navigational information services. Direct maritime affairs and local maritime affairs have strengthened coordination and linkage to jointly manage and control ship navigation, establish a disciplinary mechanism for untrustworthy ships, and prevent accidents. Shipping companies need to establish a ship inspection mechanism to regularly inspect the company’s ships to ensure the seaworthiness of the ships and the safety of navigation.

(4) Strengthen crew education and training
Directly under the maritime management agency, Nantong City Transportation Comprehensive Law Enforcement Agency, and shipping company need to increase crew training and management and enhance the crew's business capabilities. They need also to enhance the crew's legal concept, and improve the crew's competence level. Using a variety of publicity methods to increase the publicity of route and navigation laws and typical cases, focusing on improving safety awareness.

5. Summary
Through the establishment of an LNG ship port navigation risk evaluation index system, a certain LNG ship in the Lusi port area of Nantong Port is selected for risk evaluation analysis. The fuzzy comprehensive evaluation method is used to quantify the risk level of LNG ship navigation risk, and determines the risk level and various risk factors for the degree of influence on the overall risk, and a corresponding risk control plan is proposed based on the risk evaluation results. It is reasonable that the evaluation research is consistent with the objective status quo to a certain extent. I’ll deepen research on risk assessment in future study. The evaluation results and the control plan can provide reference for relevant departments to further strengthen the supervision of Nantong Port Lusi Port Area and ensure the safety of navigation.

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