Collision risk assessment in Jiangsu section of the Yangtze River based on evidential reasoning

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**Abstract.** Collision between ships is one of the dominant types of accidents in the Jiangsu section of the Yangtze River, accounting for over 60% of the accidents. An evidential reasoning (ER) approach is introduced to perform a quantitative assessment of the safety of the whole waterway by dividing it into 17 sub-sections. The Risk Influencing Factors (RIFs) including channel condition, navigation environment and navigation aids conditions are considered and further decomposed into several sub-factors. The expert knowledge is used to quantify the relative importance of the RIFs to the collision risk. The historical data is used to make the Basic Probability Assignments (BPAs) of the belief structures. The hazard index (HI) is used as a measure of collision risk. The results indicate that Kouanzhi Waters and Jiaoshan Waters carry much higher collision risk than other waters, whereas Nanjing Waters and Fanjiafan Waters have the lowest collision risk. The results are useful for the maritime safety management in the Jiangsu section of the Yangtze River.

1. Introduction

Inland waterway transportation is an important component of the integrated transportation system and it plays an important role in promoting the overall circulation of cargos worldwide. However, there are many factors affecting the safety of inland waterway transportation. Effective safety management of the maritime transportation system is the prerequisite of its sustainable development. According to the statistics on maritime accidents, the proportion of collisions between ships is more than 60% of all types of waterway transportation accidents. A lot of attention has been paid to preventing collision accidents by using measures from different aspects such as technical and organizational ones. Among those, identifying the high-risk collision waterways based on the historical accidents and the navigation condition has contributed to dealing with collision risk in a well-directed way. It is also useful for the ships in terms of understanding their risk status under different environmental conditions.

With respect to maritime risk assessment, quite a few research has been done by scholars using both qualitative and quantitative, subjective and objective approaches, and a combination of these methods. Many of them tries to identify and evaluate the Risk Influencing Factors (RIFs) based on the statistical analysis of maritime accident reports by using data mining techniques. The traffic
accidents in a specific waterway within a certain period of time can be statistically analyzed in order to find out the factors that contribute to the accident and put forward corresponding mitigation measures. However, the accident data available is, in many cases, not enough to do such research. Moreover, some other factors that are not presented in the accident reports may be also very important in the risk assessment and should be considered as well. However, different types of uncertainties are usually involved in such types of data. In order to deal with the uncertainty in risk assessment and improve the reliability of maritime risk assessment, some models have been widely used in the quantitative risk assessment of waterway transport accident, including fault/event tree analysis (FTA/ETA), the evidential reasoning (ER) approach, Bayesian belief networks (BBN), to name but a few.

Identifying the most influencing factors is a key step in risk assessment. The selection of appropriate methods generally depends on the research objective. Wan [1] used hierarchical holography modeling (HHM) and risk filtering, ranking, and management (RFRM) models to identify, filter and preliminarily evaluate a large number of risk factors of ship navigation. Fifteen key risk factors were identified to evaluate the risk level. Wang [2] used hazard identification theory to identify navigation risk factors with regard to the aspects of ship, environment and personnel, and developed the index system of risk assessment. Sun et al. [3] utilized the theory of shipping service supply chain to analyze the factors affecting the security of shipping, which are human, hardware, software and environment.

In addition, the BBN model has also gained popularity in the risk quantification [4]. For example, Montewka et al. [5] and Wan [1] evaluated navigation risk by using BBNs and applied the model to the Gulf of Finland and the Yangtze River, respectively. ER is another effective tool for quantitative risk assessment of waterway transportation under uncertainties. Sun [6] established an evaluation model based on ER for the safety of container ships navigating in the harsh environment such as strong wind. The safety evaluation index system proposed by Sun is composed of four subsystems, which are personnel, ship, environment and management. The reliability of the evaluation model is verified by an example of the risk assessment of a container ship. Dong [7] built a safety evaluation model based on ER in order to analyze the safety navigating in Tianjin port at night. There are also other methodologies that can be used to evaluate maritime risk from different perspectives, including multi index unascertained measure model [8], TOPSIS theory [9], fuzzy method [10], grey correlation analysis method [11], matter-element comprehensive evaluation method [12], cusp catastrophe model [13], etc.

The combination of two or more methods is another perspective to enhance the credibility of the risk assessment results. Based on the historical accident data, Li et al. [14] integrated logistic regression and BBN to evaluate the safety level of ships. Akyuz [15] established a hybrid accident analysis model by combining analytical network process (ANP) with human factors analysis and classification system (HFACS) to quantitatively analyze the role of human errors in maritime accidents. Faghih-Roohi et al. [16] proposed a risk assessment model for maritime transportation based on Markov chain Monte Carlo (MCMC), in which a three-state continuous-time Markov model was introduced to record and estimate the accident rate and probability. Qiu et al. [17] constructed a risk assessment model of inland waterway navigation environment based on Gaussian mixture model (GMM) and probabilistic neural network (PNN), and verify the model with 67 waterway cases. Chai et al. [18] established a quantitative risk assessment model consisting of collision frequency estimation model, event tree model and result estimation model in order to assess ship collision risk. The model also took the frequency and consequences of all possible accident scenarios into consideration.

This study tries to establish a collision risk assessment framework based on the characteristics of channels and conduct the evaluation of the collision risk of the Yangtze River. The ER method has the advantages of modeling and combining uncertain qualitative parameters and subjective beliefs in a multi-attribute framework, which is able to express the risk factors with multiple risk degrees under uncertainties, in order to achieve a more accurate assessment of the safety situation of
waterway transportation. ER is developed based on the evidence theory and multi-attribute decision analysis. It has been widely used in fault detection and data fusion. In the sector of transportation, ER has been used in the evaluation of railway transportation system [19], investment of transportation projects [20], emergency group decision-making [21], and ranking of safety inspection of roadways [22].

The rest of the paper is organized as follows: Section 2 presents the theoretical basis and methodology of evidence theory; Section 3 mainly introduces the procedure of the application of evidential reasoning to collision risk assessment, and the case study of the Jiangsu section of the Yangtze River; Finally, Section 4 concludes the paper.

2. Theoretical Basis of Evidential Reasoning

D-S theory was first proposed by Dempster [23] and Shafer [24], who expressed the degree of belief in an evidence, rather than a fixed probability value. The theory was later introduced into the ER model to deal with uncertain, imprecise, and occasionally incorrect information. ER is a method that applies D-S theory to solve the multi-attribute decision making (MADM) problems.

2.1. D–S theory

In D–S theory, it is assumed that a set of mutually exclusive and jointly exhaustive elements called the environment (Θ).

\[ \Theta = \{ \theta_1, \theta_2, ..., \theta_i, ..., \theta_n \} \]  

where, \( \theta_i \) is an element or event in the cognition framework \( \Theta \); \( n \) is the number of elements in \( \Theta \), \( (i = 1, 2, 3, ..., n.) \)

The set composed of all subsets of \( \Theta \) is called the power set of \( \Theta \), which is recorded as \( 2^\Theta \).

\[ 2^\Theta = \{ \phi, \{ \theta_1 \}, \{ \theta_2 \}, ..., \{ \theta_i \}, \{ \theta_i, \theta_j \}, ... , \{ \theta_1, \theta_2, ..., \theta_n \} \} \]  

where \( \phi \) is an empty set, \( i, j \in [1, n], i \neq j \).

(1) Basic Probability Assignment (BPA)

In D-S theory, the degree of belief in evidence is expressed by a function called evidence mass that is denoted as \( m \). This is usually called basic probability assignment (BPA). The reason of using BPA to express the belief degree is to make it became a composable and decomposable quantity variable. A essentially difference between D-S theory and probability theory is how they handle the unknown or uncertainty. Probability theory distributes probability equally, even in the absence of relevant knowledge. For example, when there are only two possibilities \( H \) and \( H' \), \( P(H) + P(H') = 1 \). This means that any information that does not support the assumption is against the hypothesis. Probability theory does not consider the uncertainty, i.e. there is no evidence to support the non-hypothesis, and it will force a value to refute the hypothesis.

In the D-S theory, the unknown is not automatically divided into non-hypothesis. In the BPA, there is only a certain probability. Any belief degree that does not belong to a specific subset is called uncertainty. D-S theory links each element of \( \Theta \) with a real number between 0 and 1. That is to say, the belief degree of a subset of \( \Theta \) can take any value between 0 and 1. D-S theory does not believe in empty sets, and the sum of the belief degree to all subsets is 1, which can be expressed as:

\[
\begin{align*}
    m(X) & \in [0, 1], X \in \Theta \\
    m(\phi) &= 0 \\
    \sum_{X \in \Theta} m(X) &= 1
\end{align*}
\]
is the BPA of event X, which represents the belief degree of evidence to X. When \( m(X) > 0 \), \( X \) is the focal element.

(2) Belief

The belief based on the BPA in \( \Theta \) is defined as:

\[
Bel(X) = \sum_{X_i \subseteq X} m(X_i)
\]  

(4)

\( \) represents the minimum level of belief in hypothesis X based on existing evidence.

(3) Plausibility

The plausibility based on the BPA \( m \) in \( \Theta \) is defined as:

\[
Pl(X) = \sum_{X_i \nsubseteq X} m(X_i)
\]  

(5)

\( \) represents the maximum level of belief in hypothesis X based on existing evidence.

(4) Belief Interval

Generally, \( 0 \leq Bel(X) \leq Pl(X) \leq 1 \). The belief interval \([Bel(X), Pl(X)]\) that is composed of \( Bel(X) \) and \( Pl(X) \) indicates the belief range of the existing evidence to the hypothesis.

2.2. Rules of Evidence Combination

D-S combination rule of evidence is used to calculate the orthogonal sum of two or more basic probability assignments, which can reflect the joint effect of evidences. D-S combination rule can achieve the overall belief degree when finding new evidence and synthesizing the existing evidence information. The combination rule is expressed as follows:

(1) Combination of two evidences:

\[
m_1 \oplus m_2(Z) = \sum_{X \cap Y = Z} m_1(X)m_2(Y)
\]  

(6)

Here, all elements satisfying the condition \( X \cap Y = Z \) are combination by evidence. By combining the BPAs, a new BPA that could represent the integration or consensus of possibly contradictory pieces of evidences can be obtained. When the two evidences are conflict too much (with a very large value of \( P \)), the D-S combination rule can be expressed as follows:

\[
m_1 \oplus m_2(Z) = \frac{\sum_{X \cap Y = Z} m_1(X)m_2(Y)}{1-P}
\]  

(7)

\[P = \sum_{X_i \nsubseteq \phi} m_1(X)m_2(Y) = 1 - \sum_{X_i \nsubseteq \phi} m_1(X)m_2(Y)
\]  

(8)

\( P \) denotes the extent of conflict among evidences, \( P = 1 \) and \( P = 0 \) representing the complete conflict and absolute concordance of evidences, respectively. \( 1-P \) is used for normalization.

(2) Combination of multiple evidences

Suppose there are \( n \) BPAs named \( m_1, m_2, \ldots, m_n \), and the focal elements \( X_i (i = 1, 2, \ldots, n) \), the combination rule can be expressed as follows:

\[
(m_1 \oplus m_2 \oplus \ldots \oplus m_n)(X) = \frac{\sum_{X_i \cap X_j \cap \ldots \cap X_n = \phi} m_1(X_i)m_2(X_j)\ldots m_n(X_n)}{\prod_{X_i \subseteq \Theta, X \neq \phi} 1-P}, \forall X \subseteq \Theta, X \neq \phi
\]  

(9)

2.3. Evidential Reasoning
A MADM problem is usually influenced by multiple factors that can be either qualitative or quantitative. In order to deal with such situation, it is necessary to understand the factors and clarify the relationship between them. The evidential reasoning has been developed for dealing MADM problems under uncertainties. ER was proposed by Yang and Singh[25], which is a method for utilization of principles of evidence theory in multi-attribute decision analysis.

Assume that the structure a MADM problem is shown in Figure 1, and the hierarchy structure has L factors denoted by F\(_i\); i = 1, ..., L with relative weights W = (w\(_1\), ..., w\(_L\)), which satisfies:

\[
\sum_{i=1}^{L} w_i = 1, w_i \geq 0
\]

Similarly, with respect to the sub-factor F\(_{ij}\) (j = 1, 2, ..., M\(_i\)) attributes of influencing factor F\(_i\), the relative weight of f\(_{ij}\) is W\(_i,j\) (w\(_{i,1}, w_{i,2}, ..., w_{i,L}\)) and the relative weight among sub factors satisfy the same requirement:

\[
\sum_{j=1}^{L} w_{i,j} = 1, w_{i,j} \geq 0, i = 1, ..., L
\]

By defining the mutual exclusion assessment grade g = \{g\(_1\), g\(_2\), ..., g\(_L\)\}, each sub-factor is assigned with a degree of belief \(\beta_{k,j,j}\). It should be noted that \(\beta_{k,j,j} \geq 0, \sum_{k=1}^{N} \beta_{k,j,j} \leq 1\). The BPA of each sub-factor to attribute g can be expressed as:

\[
S(F_{ij}) = \{(g_1, \beta_{i,1,j}), (g_2, \beta_{i,2,j}), ..., (g_k, \beta_{i,k,j}), ..., (g_N, \beta_{i,N,j})\} \quad i = 1, 2, ..., L, j = 1, 2, ..., L
\]  

The influence of each sub-factor on the factors of the high-level layer can be calculated by the following formula.

\[
m_{\bar{g},i,j} = w_{i,j} \beta_{k,j,j}, k = 1, 2, ..., N, j = 1, 2, ..., L
\]  

\[
m_{g,i,j} = 1 - \sum_{k=1}^{N} m_{\bar{g},i,j} = 1 - w_{i,j} \sum_{k=1}^{N} \beta_{k,j,j}, j = 1, 2, ..., L
\]  

\[
\bar{m}_{g,i,j} = 1 - w_{i,j}, j = 1, 2, ..., L
\]  

\[
m_{g,i,j} = w_{i,j} \left( 1 - \sum_{k=1}^{N} \beta_{k,j,j} \right), j = 1, 2, ..., L
\]  

\[
m_{\bar{g},i,j} = m_{\bar{g},i,j} + m_{g,i,j}
\]

where, \(m_{k,j} \) is the BPA of grade g\(_k\) in sub-factor F\(_{ij}\), \(m_{\bar{g},i,j} \) represents the belief that has not been assigned to set g. It is composed of two parts: \(m_{\bar{g},i,j} \) and \(m_{\bar{g},i,j} \) due to the relative importance of sub-factor j and incompleteness in the assessment of sub-factor j, respectively. That is to say,
\( \overline{m}_{g,i} \) represents the degree of factor that affects general assessment goal, and \( \overline{m}_{g,i,j} \) represents the degree of conflict between each evidence.

Through the BPA of each sub-factor, the above equations can be used to calculate \( m_{k,i,j}, m_{g,i,j}, \overline{m}_{g,i,j} \) for each factor. Then the belief distribution of multi-attribute decision problem can be obtained by evidential reasoning. The following is the procedure of evidential reasoning:

\[
m_k = p \left[ \prod_{j=1}^{\ell_i} \left( m_{k,i-j} + \overline{m}_{g,i-j} + \overline{m}_{g,i-j} \right) \right] - \prod_{j=1}^{\ell_i} \left( \overline{m}_{g,i-j} \right), k = 1, 2, \ldots, N
\]  

(16)

\[
\overline{m}_{g} = p \left[ \prod_{j=1}^{\ell_i} \left( m_{g,i-j} + \overline{m}_{g,i-j} \right) \right] - \prod_{j=1}^{\ell_i} \left( \overline{m}_{g,i-j} \right)
\]  

(17)

\[
\overline{m}_{g} = p \left[ \prod_{j=1}^{\ell_i} \left( m_{g,i-j} \right) \right]
\]  

(18)

\[
p = \left[ \sum_{k=1}^{N} \prod_{j=1}^{\ell_i} \left( m_{k,i-j} + \overline{m}_{g,i-j} + \overline{m}_{g,i-j} \right) \right] \left( N - 1 \right) \prod_{j=1}^{\ell_i} \left( \overline{m}_{g,i-j} \right)
\]  

(19)

\[
\beta_k = \frac{m_{k,i}}{1 - m_{g}}, \quad k = 1, 2, \ldots, N
\]  

(20)

\[
\beta_g = \frac{\overline{m}_{g}}{1 - m_{g}}
\]  

(21)

where \( \beta_k \) is the degree of belief degree of factor \( i \) in grade \( g_k \), and \( \beta_g \) is the extent of uncertainty.

In order to ensure the effectiveness of the ER process, in each calculation process, it is necessary to ensure that the sum of the obtained belief level and the uncertain belief level is 1, that is \( \sum_{k=1}^{N} \beta_k + \beta_g = 1 \).

3. Case Study

The "diamond" channel in the Jiangsu section is the last part of the Yangtze River before flowing into the East China Sea, whose navigable condition is the best among the whole waterways of the Yangtze River. The ship traffic flow is the largest along the Yangtze River. Its geographical distribution is shown in Figure 2. The navigation environment of this waterway section is in good condition, with deep and wide channel, stable current and good traffic control regulations (e.g. Traffic Separation Scheme, TSS). However, the collision risk in some waters is still high due to various influencing factors such as the dense traffic flow, relatively narrow channel, and restricted navigation. The navigation condition in some waterways is below the average. For example, in the Yingongzhou section, which is known as the throat of the Yangtze River, Z-shaped and the relatively narrow channel make it quite difficult for ships to keep safe. In view of the national strategy of the Yangtze River Economic Belt and the development of integration in Yangtze River Delta Region, more and more attention has been paid to the navigation safety of the ship in Jiangsu section. Collisions accounts for around 80% of all types of accidents in the Jiangsu Waterways. Many safety measures have been used, but collision accidents occur from time to time and occasionally cause very serious consequences. The main channel of the Jiangsu section is more than 390 km long, and moreover, it will reach a length of 500 km if the branches are counted in. In this paper, only the mainstream of the waterway is considered. According to the geographical location of the waterways, the Jiangsu section is divided into 17 sub waters. They are separated according to
some typical infrastructure such as bridges, ports. The segmentations of the whole waterways are presented in Figure 2.

![Figure 2. Jiangsu section of the Yangtze River.](image)

### 3.1. Hierarchical model of collision risk assessment

In order to perform a quantitative evaluation of the collision risk in each segment of the waterways as shown in Figure 2, the RIFs should be identified in the first step. Then a hierarchical structure that can reflect the relationships between the RIFs and collision risk can be constructed accordingly.

Ship collision risk assessment is a comprehensive system, which contains both qualitative and quantitative factors. It should be noted that this paper focuses on the collision risk derived from the environment, rather than the real-time ship traffic characteristics and encounter situations. In view of this, the RIFs of ship collision risk can be categorized into three types, which are channel conditions, navigation environment and navigation aid conditions. They are further decomposed into some sub-factors. For example, the sub-factors of channel conditions include width and curvature of the waterways, crossing, and river mouth. The navigation environment includes hydrometeorology, traffic flow, and peripheral facilities of channel. Furthermore, some sub-factors are further divided according to the need. For instance, hydrometeorology condition is determined according to the current, visibility and wind. The hierarchical structure of collision risk assessment model is demonstrated in Figure 3. The hierarchical model is used to calculate the collision risk of each waterway segment. Although no specific navigation scenario is considered in the model, it can be synthesized with the real-time ship collision risk.
Navigation environment (F2)

Navigation aid conditions (F3)

Width (F1,1)
Curvature (F1,2)

Crossing (F1,3)
River mouth (F1,4)

Hydrometeorology (F2,1)
Traffic flow (F2,2)

Peripheral facilities (F2,3)

Navigation aid facilities (F3,1)

Vessel traffic services (F3,2)

Current (F2,1,1)
Visibility (F2,1,2)
Wind (F2,1,3)

Vessel traffic flow (F2,2,1)
Special traffic (F2,2,2)

Anchorage or berthing (F2,3,1)

Transhipment waters (F2,3,2)

Figure 3. Hierarchical structure of collision risk assessment model considering channel characteristics.

It can be seen from Figure 3 that there are both quantitative and qualitative factors and each factor needs to be transformed into several levels according to its value range. According to some previous research and past evaluation experience [26-28], the collision risk in this paper is divided into three grades, that is \( g = \{ \text{Low, Medium, High} \} \). In order to calculate the risk, utility values of risk grades are assigned correspondingly, which is shown in Table 1.

**Table 1. Risk levels and the corresponding values**

| Risk level \( (g_k) \) | \( Du(g_k) \) |
|------------------------|------------|
| Low                    | 1          |
| Medium                 | 2          |
| High                   | 3          |

In order to quantitatively compare the collision risk, the concept of hazard index (HI) is introduced. The value of HI represents the overall risk level. For \( C_h \), its HI is calculated by the following formulas:

\[
E(C_h) = \sum_{k=1}^{N} \beta_k (C_h) Du(g_k) \quad (22)
\]

\[
E_{\text{max}} (C_h) = \left( \beta_N (C_h) + \beta_k (C_h) \right) Du(g_N) + \sum_{k=1}^{N-1} \beta_k (C_h) Du(g_k) \quad (23)
\]

\[
E_{\text{min}} (C_h) = \left( \beta_1 (C_h) + \beta_k (C_h) \right) Du(g_1) + \sum_{k=2}^{N} \beta_k (C_h) Du(g_k) \quad (24)
\]

\[
E_{\text{avg}} (C_h) = \frac{E_{\text{max}} (C_h) + E_{\text{min}} (C_h)}{2} \quad (25)
\]

The above equations express the average risk values, and the upper and lower bounds of the collision risk under uncertainties as well. When there is no uncertainty in the BPA of the factors, the \( \beta_k (C_i) = 0 \), \( \text{HI} = E_{\text{avg}} (C_i) = E(C_i) \).
3.2. Attribute weight assignments

Noting that the degree of influences of RIFs on collision risk are not equally distributed, thus before using ER to evaluate the collision risk of each waters, it is necessary to determine the relative weight of the factors in each level of the hierarchical structure. This is done by synthesizing the expert knowledge from the Jiangsu Maritime Safety Administration (MSA) and National Engineering Research Center for Water Transport Safety (WTS Center), Wuhan University of Technology. A total of 12 experts were invited to give their subjective opinions through questionnaires. The detail information of the experts is shown in Table 2. They are required to rate each factor according to its relative importance over other factors. After receiving the questionnaire, the answers are reviewed and analyzed. If they did not reach a consistency (their opinions have strong conflicts), a second round questionnaire is prepared accordingly. This process will be repeated until the experts reach a certain degree of agreement and the relative weights of all risk factors can be determined.

| Number | Working/Research Area                | Position       | Working years |
|--------|-------------------------------------|----------------|---------------|
| 1      | River Traffic Supervision           | Director       | 15            |
| 2      | River Traffic Supervision           | Deputy director| 12            |
| 3      | River Traffic Supervision           | Clerk          | 5             |
| 4      | Water Rescue and Emergency Response | Clerk          | 10            |
| 5      | Channel Design                      | Section Chief  | 12            |
| 6      | Ship Collision Avoidance            | Researcher     | 8             |
| 7      | Ship Traffic Safety                 | Researcher     | 9             |
| 8      | Ship Collision Avoidance            | Deputy Researcher | 8       |
| 9      | Ship Traffic Safety                 | Deputy Researcher | 7       |
| 10     | Ship Traffic Safety                 | Assistant Researcher | 4       |
| 11     | Ship Operation Management           | Deputy Researcher | 5       |
| 12     | Risk Management                     | Deputy Researcher | 8       |

The results from each expert are synthesized using the Delphi method, so that the relative weights of collision risk factors in each layer can be determined. It should be noted that the sum of the factor weights for each factor in the same level should be normalized. The details of the weights are shown in Table 3. It can be seen that channel conditions and navigation environment have much more influence on collision risk than navigation aids conditions. With respect to the 2nd level, the width and curvature of the channel as well as the volume of the traffic flow are more important in evaluating the collision risk compared to others.

| Target                                      | 1st Level | 2nd Level | 3rd Level |
|---------------------------------------------|-----------|-----------|-----------|
| Collision risk in the Jiangsu section of the Yangtze River | 0.45      | Width 0.41 | \        |
|                                             |           | Curvature 0.4 | \        |
|                                             |           | Crossing 0.09 | \        |
|                                             |           | River mouth 0.1 | \        |
| Navigation environment                       | 0.45      | Hydrometeorology 0.25 | Current 0.3 |
|                                             |           | Visibility 0.4 | Wind 0.3    |
In order to perform the combination of the RIFs from bottom to the top in the hierarchical structure, all the RIFs should be classified into three levels as in Table 1 according to the range of the factors. Table 4 presents the guideline for the standards of specifying the three levels for each sub-factor. When determining the BPA of each influencing factor of the waters, the belief can be carried out according to the corresponding standards in Table 4. Taking Liuhe Waters and Kouanzhi Waters as examples, the information of 13 influencing factors such as width, curvature and visibility can be collected and analyzed. The BPA can be determined according to the standards. The results are shown in Table 5. It can be seen that the BPA of each factor are different. Some factors only have belief value in one risk level and some others are distributed in two or more levels. It is noted that the total belief must not be larger than 1. For example, when considering the crossing of Liuhe Waters, the belief degree of low risk is 0.1, and the belief of medium risk is 0.8, which means that due to the lack of evidence (cognition, lack of experience, etc.), there is 0.1 degree of belief that has not been assigned to any risk levels. This also indicates that such belief structures carry certain uncertainties. The BPAs of other factors can be obtained in a similar way.

| Factor          | Sub-factor          | Risk          | Low (g₁) | Medium (g₂) | High (g₃) |
|-----------------|---------------------|---------------|----------|-------------|-----------|
| Traffic flow    |                     | Vessel traffic flow | 0.5      | 0.68        |           |
| Peripheral      |                     | Special traffic flow | 0.25     | 0.32        |           |
| facilities of   |                     | Anchorage,     |          |             |           |
| channel         |                     | berthing      |          |             |           |
|                 |                     | Transhipment  |          |             |           |
|                 |                     | waters        |          |             |           |
| Navigation      | 0.1                 | Vessel traffic system | 0.5     | 0.48        |           |
| System          |                     | Vessel traffic system | 0.5     | 0.52        |           |

Table 4. A general guideline for collision risk level.

- The channel width is relatively large, and the ship breadth is smaller.
- The channel width is suitable for the ship.
- The channel width is smaller, but the ship breadth is larger.
- 0°≤ The maximum steering angle ≤16°
- 16°< The maximum steering angle ≤21°
- The maximum steering angle >21°
- None
- 1 low-flow river mouths and 1 medium-flow river mouth or 3 low-flow river mouths
- Total number of river mouths ≥4 or high-flow river mouth ≥1 or medium-flow river mouths ≥2
- Slowly current
- There are
- The current is
and with little pressure is almost impervious to the tides. occasional rapids with stable flow direction and pressure, which are affected by tides. swift, the flow direction is changeable, the flow pressure is high, and it is greatly influenced by the tides.

| Visibility | Foggy days ≤6 per year | 6< Foggy days≤12 per year | Foggy days >12 per year |
|------------|------------------------|----------------------------|------------------------|
| Wind       | 6 or above level wind≤9 | 9< 6 or above level wind≤12 | 6 or above level wind >12 |
| Vessel Traffic Flow | Vessel traffic flow≤1200 ships/day | 1200<vessel traffic flow≤1400 ships/day | Vessel traffic flow>1400 ships/day |
| Special Traffic Impact | No passenger ferry, fewer construction ships, and almost no sand dredgers and fishing boats. | Some passenger ferry, occasional construction ships, sand dredgers and fishing boats. | Busy passenger ferry, frequent construction ships, sand dredgers, fishing boats actively. |
| Anchorage, Berthing | 0≤The area of anchorage and berthing ≤2 | 2<The area of anchorage and berthing≤6 | The area of anchorage and berthing >6 |
| Transhipment waters | None | The transhipment area is small and far away from the channel. | The transhipment area is large and close to the channel. |

| Navigation aid conditions | Navigational Aids | Vessel Traffic Service |
|---------------------------|------------------|------------------------|
| The navigation aid facilities are complete and timely maintained. | The navigation aid facilities are relatively complete and maintenance is relatively timely. | The navigation aid facilities need to be improved and maintenance is not timely. |
| VTS is fully covered and the signal is perfect. Information is released in a timely manner through multiple | VTS has full coverage and good signal, timely information release, general supervision, and good execution by | VTS is partially covered, with poor signal, lack of supervision, and the execution ability of relevant personnel needs |
channels. Relevant personnel to be improved.
Supervision is strong and relevant personnel are in place.

Based on the BPAs of all the sub-factors in the 17 waterways as well as the relative weights of each factors from expert knowledge, the ER algorithm can be performed in a bottom-up mode as shown in Figure 3. The algorithm starts from the third layer and upwards layer by layer. The outputs of each layer are used as the inputs of the upper layer. Finally, the HI of each waters are obtained. The results are concluded in Table 6. It can be seen from the table that the value of HI in Kouanzhi waters, Jiaoshan waters, Nantong waters, Fujiangsha waters, Dantuzhi and Yizheng waters are larger than 2. It means that the collision risk of them are at the middle-to-high level. The Kouanzhi waters and Jiaoshan waters are among the highest risk levels. Their HI values are larger than 2.5, which indicates a relative high collision risk. The HI of other waterways are between low-to-medium risk levels. Nanjing waters and Fanjiafan waters are the two areas with the lowest collision risk in the Jiangsu section.

Table 5. BPA of Liuhe and Kouanzhi waters.

| Factor                        | Sub-factor         | BPA (Low, Medium, High) | Liuhe Waters | Kouanzhi Waters |
|-------------------------------|--------------------|-------------------------|--------------|-----------------|
| Channel conditions            | Width              | (0.5, 0.5, 0)           | (0, 0.6, 0.4) |
|                               | Curvature          | (0.45, 0.45, 0)         | (0, 0, 1)    |
|                               | Crossing           | (0.1, 0.8, 0)           | (0, 0.8, 0.2) |
|                               | River Mouth Current| (0, 0.1)                | (0.01, 0.9)  |
| Hydro Meteorology             | Visibility         | (0, 0, 0.97)            | (0, 0.89)    |
| Traffic Flow                  | Wind               | (0, 0, 0.935)           | (0.88, 0, 0) |
|                               | Vessel Traffic     | (0.8, 0.2, 0)           | (0.15, 0.85) |
|                               | Special Traffic    | (0, 0.1, 0.9)           | (0.8, 0.2)   |
|                               | Impact Anchorage,  | (0, 0.95)               | (0.25, 0.65) |
|                               | Berthing Transhipment| (1, 0, 0)              | (0, 0, 1)    |
| Navigational aids             | Navigational Aids  | (0.7, 0.3, 0)           | (0.5, 0.3, 0.2) |
|                               | Vessel Traffic     | (0.9, 0.1, 0)           | (1, 0, 0)    |

The state of channel conditions and navigation environment lead a relatively high collision risk level of Kouanzhi waters. The maximum turning angle of the channel is about 30°, and 18 days on average of a year are of foggy weather. It has 3 anchorages and 2 mooring areas; there are crossing and river mouth, which exacerbate the impact of water flow on risk to some extent, and the impact of vessel traffic flow and special traffic flow is also at a relatively high level. On the contrary, the
state of each factors is relatively moderate in Fanjiafan waters, such as relatively gentle lines, no need to worry about ferry and anchoring ships when sailing here.

It should be noted that the collision risk assessment is largely based on the analysis on the channel conditions, navigation environment and navigation aids from a macro perspective. The results can be further synthesized with the collision risk evaluation from a micro perspective. By doing so, the reliability of the results can be promoted and collision risk can also be evaluated in a real-time mode.

| Waters                      | Risk distribution | Expected risk | Hazard index (HI) | Ranking |
|-----------------------------|-------------------|---------------|------------------|---------|
| Liuhe waters                | 0.52 0.275 0.184 0.021 | 1.622 1.685 1.643 | 1.664 13 |
| Baimaoshia waters          | 0.507 0.228 0.256 0.01   | 1.729 1.758 1.739 | 1.749 10 |
| Tongzhousha waters         | 0.347 0.322 0.295 0.036 | 1.876 1.985 1.912 | 1.949 7  |
| Nantong waters              | 0.094 0.365 0.511 0.029 | 2.358 2.446 2.387 | 2.417 3  |
| Liuhaihaisha waters        | 0.46 0.342 0.167 0.031 | 1.645 1.738 1.676 | 1.707 11 |
| Jiangfusha waters          | 0.073 0.413 0.478 0.036 | 2.332 2.441 2.368 | 2.405 4  |
| Jiangyin waters             | 0.464 0.189 0.319 0.028 | 1.798 1.883 1.826 | 1.855 8  |
| Taixing waters              | 0.587 0.206 0.173 0.034 | 1.518 1.62 1.552 | 1.586 14 |
| Kouanzhi waters            | 0.059 0.201 0.717 0.023 | 2.612 2.681 2.635 | 2.658 1  |
| Dantuzhi waters             | 0.227 0.132 0.61 0.031  | 2.32 2.414 2.351 | 2.382 5  |
| Jiaoshan waters             | 0.181 0.105 0.686 0.028 | 2.449 2.533 2.477 | 2.505 2  |
| Yizheng waters              | 0.199 0.528 0.235 0.039 | 1.958 2.075 1.997 | 2.036 6  |
| Longtan waters              | 0.415 0.37 0.179 0.036 | 1.691 1.799 1.727 | 1.763 9  |
| Caoxiexia waters            | 0.435 0.39 0.139 0.036 | 1.631 1.74 1.667 | 1.704 12 |
| Nanjing Yangtze River Bridge waters | 0.556 0.307 0.108 0.029 | 1.494 1.58 1.522 | 1.551 15 |
| Nanjing waters              | 0.645 0.274 0.064 0.016 | 1.387 1.435 1.403 | 1.419 16 |
| Fanjiafan waters            | 0.684 0.222 0.073 0.021 | 1.348 1.41 1.368 | 1.389 17 |

4. Conclusion
As one of the busiest waterways in the Yangtze River, the ship traffic in Jiangsu section is very complex and collisions are the dominant types of accident. A few of them have resulted in serious consequences. In order to perform a quantitative analysis on the collision risk in different segments of the waterway, the ER method is introduced. A hierarchical structure reflecting the influence of different RIFs on collision risk is constructed. The HI is also introduced as a measure of collision risk. On the basis of the structure, the relative importance of risk factors is obtained using Delphi analysis of the expert knowledge. Finally, the ER approach is used to synthesize the expert knowledge with historical data. The results indicate that the risk values of some waterways are much higher than others, which are Kouanzhi waters, Jiaoshan waters. This indicates that special attention should be paid to them during the safety management practices. Nanjing waters and Fanjiafan waters have the lowest collision risk values, which indicate that these two areas are safer with respect to collision risks.

It should be noted that the paper studies the collision risk mainly from a macro perspective. They can be further synthesized with the analysis of real-time encounter situations among ships, as well
as the real-time traffic flow characteristics. By doing so, the proposed model can generate more precise results on the collision risk.

Acknowledgments
The research was supported by National Key Technologies Research & Development Program (2017YFE0118000), Funds for International Cooperation and Exchange of the National Natural Science Foundation of China (51920105014), the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 730888 (RESET) and the National Natural Science Foundation of China (51909202; 51609228).

References:
[1] Wan Z Q 2017 Research on ship navigation risk identification, filtering and evaluation (Harbin: Harbin Engineering University)
[2] Wang W J 2015 Study of evaluation and prediction of navigation risk of Qingdao port. (Dalian: Dalian Maritime University)
[3] Sun L Zhang, H W, Liu W and Chen F 2018 Research on risk assessment and control of inland navigation safety International Journal of System Assurance Engineering and Management 9 729-38
[4] Kabir S and Papadopoulos Y 2019 Applications of Bayesian networks and Petri nets in safety, reliability, and risk assessments: A review Safety Science 115 154-75
[5] Montewka J, Ehlers S, Goerlantd F, Hinz T, Tabri K and Kujala P 2014 A framework for risk assessment for maritime transportation systems—A case study for open sea collisions involving RoPax vessels Reliability Engineering and System Safety 124 142-57
[6] Sun J 2013 Safe assessment of container ship navigating in Heavy sea based on evidence theory (Dalian: Dalian Maritime University)
[7] Dong R H 2016 Safety evaluation of ship navigation in night based on evidence theory (Dalian: Dalian Maritime University)
[8] Li W, Hu S P, You Q H and Xi Y T 2009 Unascertained measure model for port traffic risk assessment Journal of Shanghai Maritime University 30 13-17+21
[9] Ma Q D, Jiang F C, Wang Q P and Wan C 2018 Improved TOPSIS Based Model for Risk Assessment on Ship Navigation Environment Navigation of China 41 86-90
[10] Balmat J F, Lafont F, Maifret R and et al 2009 MAritime RISk Assessment (MARISA), a fuzzy approach to define an individual ship risk factor Ocean Engineering 36 1278-86
[11] Zhang S H, Zhu J, Li W D, Wang L, Liu D W and Wang T W 2019 Navigation risk assessment method based on flow conditions: A case study of the river reach between the Three Gorges Dam and the Gezhouba Dam Ocean Engineering 175 71-9
[12] Zhu J S, Huang C and Ma Y 2019 On the environmental risk assessment of ships navigating through channel waters at night Journal of Safety and Environment 19 43-8
[13] Jiang D, Hao G Z, Huang L W and Zhang D 2016 Use of Cusp Catastrophe for Risk Analysis of Navigational Environment: A Case Study of Three Gorges Reservoir Area PLOS ONE 11 e0158482
[14] Li K X, Yin J B, Bang H S and Yang Z L 2014 Bayesian network with quantitative input for maritime risk analysis Transportmetrica A: Transport Science 10 89-118
[15] Akyuz E 2017 A marine accident analyzing model to evaluate potential operational causes in cargo ships Safety Science 92 17-25
[16] Faghih-Roohi S, Xie M and Kien M N 2014 Accident risk assessment in marine transportation via Markov modelling and Markov Chain Monte Carlo simulation Ocean Engineering 91 363-70
[17] Qiu W Q, Tang C B and Tang Q R 2019 Navigation environment risk assessment of uncertain inland waterway Navigation of China 42 52-55+67
[18] Chai T, Weng J X and Xiong D Q 2017 Development of a quantitative risk assessment model for ship collisions in fairways Safety Science 91 71-83
[19] Huang W C, Liu Y K, Zhang Y, Zhang Xu, M H De, Dieu G J, Antwi E and Shuai B 2020 Fault Tree and Fuzzy D-S Evidential Reasoning combined approach: An application in railway dangerous goods transportation system accident analysis Information Sciences 520 117-29
[20] Kronprasert N and Talvitie A 2014 Reasoning-building process for transportation project evaluation and decision making Transportation Research Record: Journal of the Transportation Research Board 2453 11-21
[21] Wu B, Yan X P and Wang Y 2016 Emergency decision-making method for handling an out-of-control ship in inland water in case of uncertain information Journal of Harbin Engineering University 37 908-14
[22] Sadeghi A, Farhad H, Mhammadzadeh Moghaddam A and Jalili Qazizadeh M 2018 Identification of accident-prone sections in roadways with incomplete and uncertain inspection-based information: a distributed hazard index based on evidential reasoning approach Reliability Engineering & System Safety 278-89
[23] Dempster A P 1967 Upper and lower probabilities induced by multivalued mapping The Annals of Mathematical Statistics 38 325-39
[24] Shafer G 1976 A mathematical theory of evidence (Princeton: Princeton University Press)
[25] Yang J B and Singh M G 1994 An evidential reasoning approach for multiple-attribute decision making with uncertainty IEEE Transactions on Systems Man & Cybernetics 24(1) 1-18
[26] Hilgert H and Baldauf M 1997 A common risk model for the assessment of encounter situations on board ships Deutsche Hydrographische Zeitschrift 49 531-42
[27] Perera L P and Guedes Soares C 2015 Collision risk detection and quantification in ship navigation with integrated bridge systems Ocean Engineering 109 344-54
[28] Liu J G, Cui J, Zhou H, Wan Z Q and Cao J 2019 Research on ship navigation risk assessment method based on HHM-RFR Chinese Journal of Management Science 27 174-83