

Challenges and New Developments in Maritime Risk Assessment

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Abstract: Concerns have been raised to navigational safety in China because the throughput and the passing ships have been rapidly increasing during the past few years while accidents such as collisions, groundings, overturns, oil-spills and fires have occurred repeatedly, causing serious consequences. Though techniques for risk assessment such as formal safety assessment (FSA) have been acknowledged to be a possible way to eliminate or reduce the number of accidents and broadly used in the shipping industry nowadays around the world, there are certain challenges existing when an effective risk assessment is carried out. This paper will address some of the obstacles in maritime risk studies, e.g. lack of data and fuzziness by introducing a few recent case studies in the Yangtze River, China's largest and the world's busiest inland waterway. Attempts made in this paper are to demonstrate how advanced methodologies can facilitate maritime risk assessment under high uncertainties.

Keywords: Maritime risk assessment, uncertainty, Yangtze River.

1. INTRODUCTION

The research of maritime risk assessment dates from the study on the risk of collision at sea, when methods of accident investigation and analysis were generally used to identify specific causes of marine accidents, and then to put forward countermeasures for the purpose of preventing similar incidents. This form of maritime investigation report is still in use in some fields so far [1]. Safety index method, as the second generation of maritime risk assessment approach, has been widely used in China these years, to evaluate the safety status of waterway transportation in different areas with respect to five accident indicators, namely, number of accident, direct economic loss, death toll, number of injury and number of wreck ship. For example, Changjiang (the Chinese name for the Yangtze River) Maritime Safety Administration (MSA) is still adopting these five indexes in the evaluation of safety level of local MSAs within its jurisdiction. The two methods mentioned above mainly focus on the accidents occurred rather than the condition of risk influencing factors in the system when conducting the maritime risk assessment, which results in the study being limited in a post evaluation stage.

After the 1990s, with the increasing requirements on preventive safety management, a number of studies in maritime risk assessment have been carried out at home and abroad. Among them, one milestone event is that International Maritime Organization (IMO) enforced Formal Safety Assessment (FSA) as a formal method in risk decision making by the release of a guideline document [2]. Since then, risk assessment and safety analysis have broken through the limitation of accident evaluation. Related research can be classified into several different categories in terms of the research objects. Each type of the research concentrates on a particular target such as ship type, navigation area, accident type, causal mechanism and safety management.

In view of the different severity levels of damage caused by marine accidents, passenger ships, chemical tankers and fishing boats have been considered as major research priorities, and therefore numerous studies have been carried out on them. Hong and Yu [3] evaluated the operation safety of ro-ro passenger ships in China by a quantitative method. Hideyuki and Susumu [4] analyzed hazards associated with loading and unloading of liquefied natural gas (LNG) and LNG spills using a consequence assessment method. Piniella and Fernández-Engo [5] assessed the level of risk existing in

the fishing fleet of Andalusia in SW Spain, while some working instruments for the detection and reduction of various potential hazards as well as safety control plans were presented.

Researchers pay more attention on the navigation area with relatively large ship traffic volume and restricted navigational condition. Accordingly, the research focus is mainly on straits or port water area. Özgecan and Birnur [6] conducted safety analysis on the traffic condition of the Strait of Istanbul and the key factors that influenced maritime risk were identified. Gao and Wu [7] quantitatively analyzed the critical degree of channel environment in the water area of Xiamen inner port. Zhang [8] carried out an environmental risk assessment on the accidents like collisions, groundings and overturns in Tianjing port navigable waters.

Research on marine accidents is always crucial for maritime safety studies. Psarros, Skjong and Eide [9] described the risk status of waterway based on an analysis of marine accident data. Celik, Lavasani and Wang [10] developed a risk modeling based approach to enhance the execution process of shipping accident investigation. Mou, Van der Tak and Ligteringen [11] proposed a method to reduce the collision risk in busy waterways through the application of Automatic Identification System (AIS) data.

Waterway transportation system (WTS) has been regarded as a complex multi-factor system composed of sub-systems such as human, vessel, environment and management. According to the statistics, the most important factor that directly leads to marine accidents is the human error, which therefore has been attracting attentions worldwide in the study of accident-causing mechanism of WTS. Konstandinidou and Nivolianitou [12] applied the Cognitive Reliability Error Analysis Method (CREAM) with fuzzy logic for human reliability analysis. Liu [13] and Sheng [14] researched the human reliability in collision avoidance and stable condition for the human-ship system, respectively.

In China, maritime authorities and academics have conducted extensive and comprehensive discussions and research on the countermeasures of maritime safety management. Zheng [15] presented a performance enhancement approach for maritime administration by introducing an Analytic Hierarchy Process (AHP). A method of Marine Safety Management (MSM) based on safety evaluation was produced by Hao [16].

2. MARITIME RISK ASSESSMENT METHODS

2.1 Formal Safety Assessment (FSA)

By adopting the standardized five steps, namely, identification of hazards, risk analysis, risk control options, cost benefit assessment and recommendations for decision making, FSA conducts a comprehensive evaluation in terms of ship design, inspection, operation and navigation, aiming at enhancing maritime safety in order to protect life, health, marine environment and onboard property [2]. The framework is shown in Fig. 1.

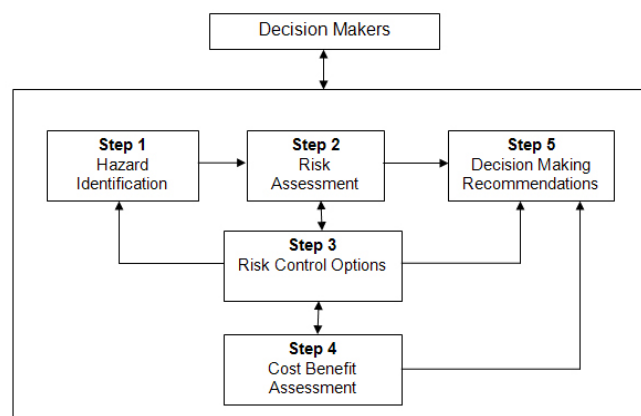


Figure 1: FSA Framework

In the early 21st century, Wang published a series of review articles about the FSA method, pointing out the application prospect of this method in the field of maritime risk assessment [17]. Moreover, several case studies were conducted under the framework of FSA, in combination with other safety evaluation methods. In China, Duan, Hu and other researchers [18, 19] also carried out similar studies.

2.2 Hierarchical Models

Taking the safety status or risk level of WTS as the research goal followed by establishing a multiple index evaluation system up to down based on risk influencing factors, are the main processes of quantitative risk evaluation which has been widely used worldwide. It is also the main approach for maritime risk assessment in China.

Based on the hierarchical model, fuzzy evidential reasoning [20] and fuzzy comprehensive evaluation method [21] have been proposed by research scholars abroad in recent years, while the most common used methods in China at present are grey system theory [22] and fuzzy AHP [23].

2.3 Network Models

Compared to hierarchical models, network models show superiority in reflecting the interaction between various risk influencing factors, which have thus been valued by more and more researchers. Among the relevant studies, Bayesian Network (BN) model is the most popular one due to its advantages in dealing with uncertainties.

Yang, Bonsall and Wang [24] put forward a method to combine fuzzy logic when applying BN model, for the purpose of incorporating qualitative and quantitative data. Norrington et al. [25] evaluated the reliability of ship search and rescue operation using BN method. Trucco et al. [26] developed a Bayesian Belief Network (BBN) model considering both human and organizational factors and WTS was chosen as a case study to illustrate the application of the proposed model.

2.4 Resilience Engineering

The concept of resilience was introduced about two hundred years ago, but with the development of society and economics, the definition of resilience varied. The common concept was from ecosystem, [27], regarded as the measure of its ability to absorb changes and remain still. In the field of engineering, resilience was defined as the intrinsic ability of a system to adjust its functioning prior to operation, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions [28]. From the aspect of risk, resilience was defined as the ability of a system to withstand a major disruption with accepted degradation parameters and to recover within an acceptable period [29, 30]. As an alternative approach, resilience is gradually used internationally in maritime risk assessment, but there is rare research in China.

2.5 Risk Assessment with Uncertainty

Uncertainty is one of the biggest challenges for maritime risk assessment. As a complex system affected by human, ship machinery, environment and management, WTS is generally analyzed from both engineering and organizational perspectives. With respect to the uncertainties involved in the risk assessment, the main challenges are: (1) uncertainty from the cognitive component of WTS, (2) uncertainty from data incompleteness, and (3) sensitivity to the uncertainty of the input data.

The above uncertainties bring difficulties to implement quantitative maritime risk assessment. For this reason, a lot of researchers have turned their attentions to uncertainty analysis in maritime risk assessment. Goerlandt and Kujala [31] mentioned that probability and indicator based risk assessment does not usually result in a reliable risk picture. In addition, another latest work can be seen in a vessel

traffic statistical study in Canary Islands [32] and an uncertainty analysis of chemical tanker collisions in the Gulf of Finland [33].

3. CASE STUDIES

A few recent cases in the Yangtze River are shown in this section to demonstrate how advanced methodologies, e.g. AHP, ER and BN can facilitate maritime risk assessment in the longest river in China under certain uncertainties.

3.1 Navigational risk assessment of the Yangtze River

Uncertainties are involved when evaluating the navigational risk of Inland Waterway Transportation System (IWTS) that objective data collection would be usually infeasible when assessing the factors involving human and management aspects. As the data of human and management aspects may not always be available, one feasible way of handling such situation is to collect subjective data by using linguistic assessment. Fuzzy set theory is well suitable for modeling subjective linguistic variables and dealing with discrete problems. In this case, a subjective method is proposed combining AHP with discrete fuzzy sets to deal with navigational risk assessment of the Yangtze River [34].

Four main aspects of IWTS, namely, human, vessel, environment and management, and their sub-systems/elements are identified based on expert judgments and literature review by which a hierarchical structure for navigational risk assessment is established as shown in Fig. 2.

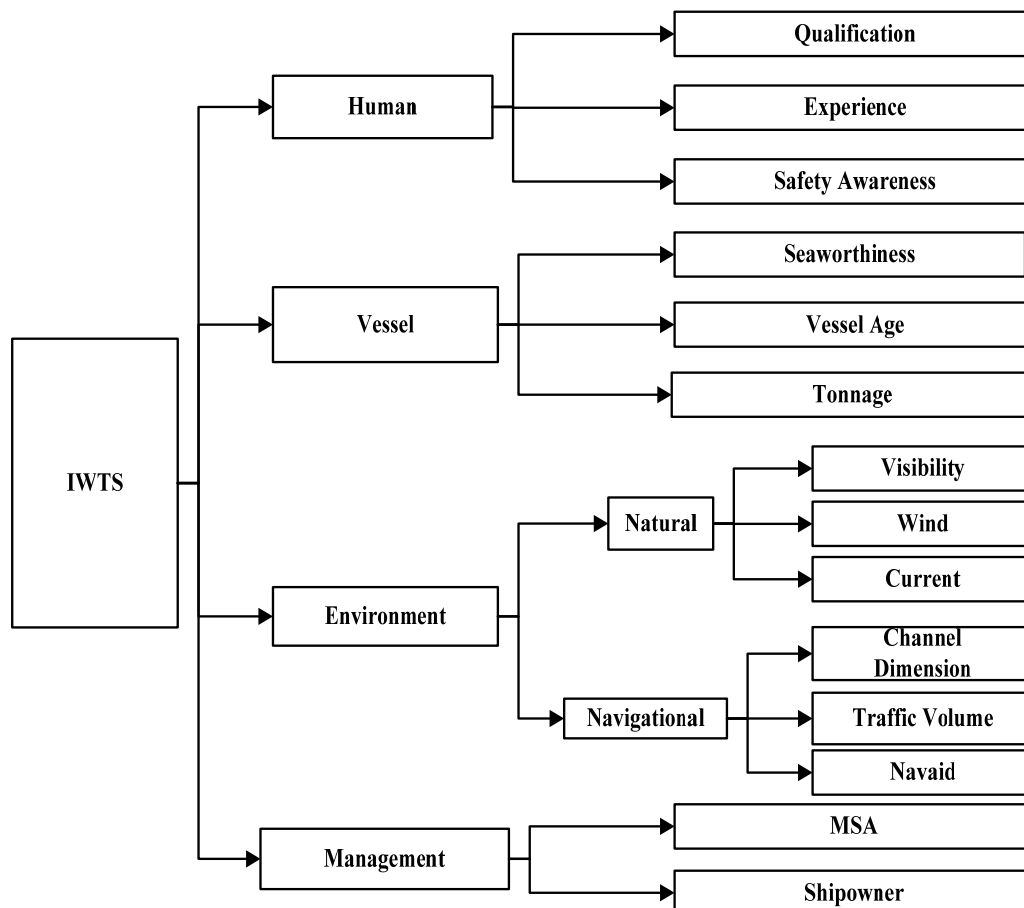


Figure 2: The AHP Structure of IWTS Modeling

AHP method is implemented so that the safety critical elements (SCEs) can be identified by multiplying the weighting vectors of relevant associated upper level elements, the normalized overall weights of each element/factor are shown in Table 1.

Table 1: Normalized Overall Weights

Aspects of IWTS		Influencing Factors	Overall Weight	Rank
Human		Experience	0.065	6
		Qualification	0.161	2
		Safety Awareness	0.207	1
Vessel		Tonnage	0.059	8
		Vessel Age	0.061	7
		Seaworthiness	0.084	4
Environment	Natural	Current	0.015	13
		Wind	0.025	12
		Visibility	0.034	11
	Navigational	Traffic Volume	0.014	14
		Navaid	0.044	10
		Channel Dimension	0.106	3
Management		MSA	0.060	9
		Shipowner	0.065	6

As per the result of Table 1, four influencing factors, namely, Safety Awareness, Qualification, Channel Dimension and Seaworthiness, are identified as the SCEs in terms of navigational risk of the Yangtze River with respect to their comparatively high normalized overall weights.

The hierarchical model is further applied for maritime risk assessment in a follow up study incorporating Fuzzy Rule Base and Evidential Reasoning (FRBER) methodologies [35]. In this case, uncertainty is mainly brought by two problems. One is that qualitative and quantitative should be dealt with simultaneously. Another one is that the mapping process between the lower and upper bound Safety Critical Factors (SCFs) is difficult to be carried out by historical data. In the model, fuzzy rules are used to establish the relationships among SCFs. For example, the relationship between channel dimension and navigational environment can be expressed as “IF Channel Dimension is Very Good, THEN Navigational Environment is Very Good with probability 0.5 and Good with probability 0.5”. Other relationships are built in similar ways. After that, Evidential Reasoning (ER) is used to synthesize the activated fuzzy rules so as to obtain the final result of navigational risk level.

The proposed model is further used in navigational risk assessment for three different regions of the Yangtze River, which are Region A (the upper stream), Region B (the midstream) and Region C (the downstream), respectively. The results can be seen in Fig. 3. The navigation safety situation is illustrated in five grades, which are “Very Poor”, “Poor”, “Average”, “Good” and “Very Good”. Fig. 3 shows the belief degree of safety to each grade in terms of the three regions.

One of the biggest advantages for FRBER is that it can facilitate risk assessment even when the input data is in a fuzzy and uncertain version. However, it can be seen that the results in Fig. 3 are expressed with discrete belief degrees which bring difficulty to compare the safety level of the three regions. The concept of utility value was then introduced to transform the belief structures into crisp values by assigning a utility value to each grade. By doing so, it can be seen in Table 2 that Region C has the best safety situation while Region B carries the highest navigational risk. This is in harmony with the historical data that marine accidents are more likely to happen in the midstream of Yangtze River, especially during the dry season, thus partially validating the proposed method.

The novel and flexible approach presented in this study could be applied for modeling IWTS behaviors in other regions such as America and Europe once further tested. The results of this study provide useful information for the shipping industry in order to reduce the navigational risk by estimating various scenarios of an IWTS.

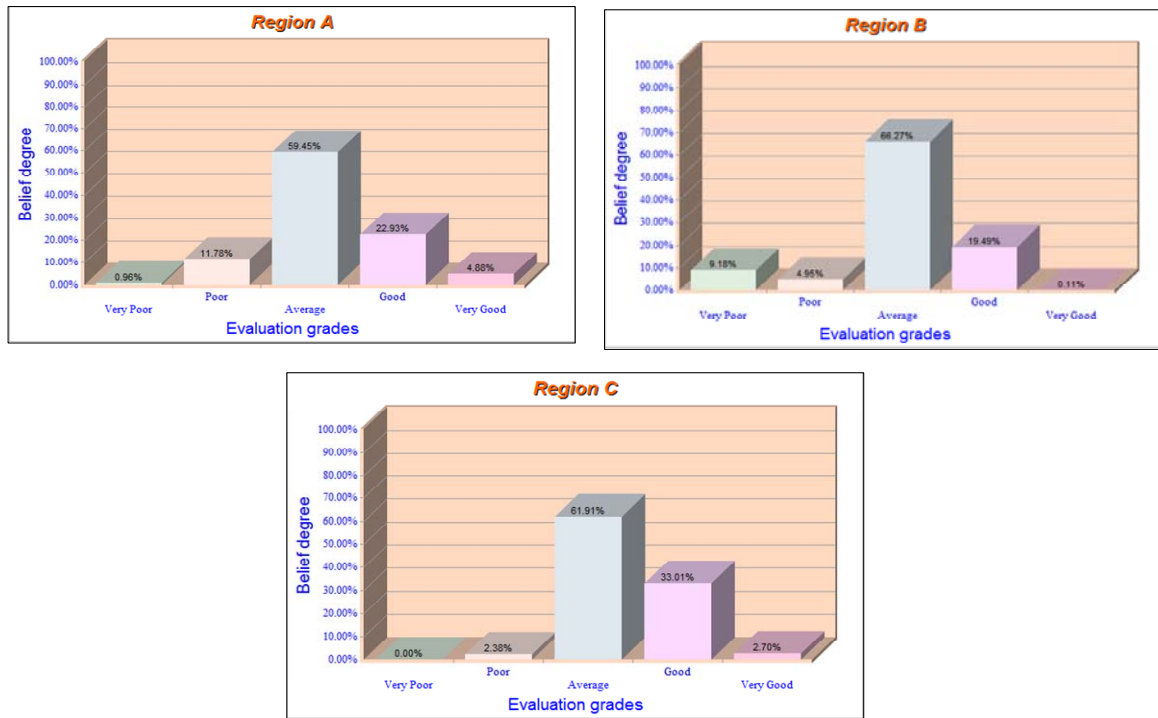


Figure 3: Comparison of navigational risk for three regions of the Yangtze River

Table 2: Overall Utility Value Ranking

Areas	Grades					Overall Utility Value	Rank
	Very Poor 0	Poor 0.25	Moderate 0.5	Good 0.75	Very Good 1		
Region A	0.010	0.118	0.595	0.229	0.049	0.548	2
Region B	0.092	0.050	0.663	0.195	0.001	0.491	3
Region C	0	0.024	0.619	0.330	0.027	0.590	1

3.2 Congestion risk assessment of the Yangtze River

Inland waterways suffer from congestion problems especially in certain bottlenecks such as port and lock areas. Due to capacity problems in the field of container loading and discharging at terminals, inland navigation has to deal with long waiting time, which causes severe problems to liner services [36]. The lock capacity could also be a constraint to inland waterway transportation. Traffic congestions often occur in the lock areas of the Upper Mississippi River, resulting in huge delay costs for shipping [37].

Channel congestion of the Yangtze River is generally caused by marine accidents such as groundings, which mostly occur during the dry season when channel dimension is limited. In this case study [38], uncertainty was mainly brought by the fact that the relationships among congestion risk and SCFs are not clear. Another concern in terms of uncertainty was how to identify the dominant factors that affect congestion most. Thus, BN approach was introduced for congestion risk assessment to carry out interaction modeling among the identified SCFs. The structure of BN for congestion risk was trained by historical accident data from January 1st of 2006 to December 31st of 2010, during which 663 accidents were reported and 66 of them caused channel congestion.

In general, congestion in the Yangtze River was caused by many factors. It may be caused by high traffic volume, severe environmental conditions such as poor visibility, ship accident which blocks the waterway and confined channel dimension in the dry season. By correlation analysis, the BN structure was composed of eleven parameters or nodes, including Ship Type, Gross Tonnage, Shipowner, Date and Time, Accident Site, Accident Type, Accident Severity, Wind, Current, Visibility and Congestion

situation. A Congestion Risk Index (CRI) was then introduced to measure the congestion risk of the Yangtze River by taking into account both probability and consequence of congestion. The BN structure trained from historical data is shown in Fig. 4. The experts' knowledge was also obtained by a focus group study, which was used to further modify the Conditional Probability Tables (CPTs) of the BN model. The model was used to evaluate congestion risk of the upstream, midstream and downstream of the Yangtze River.

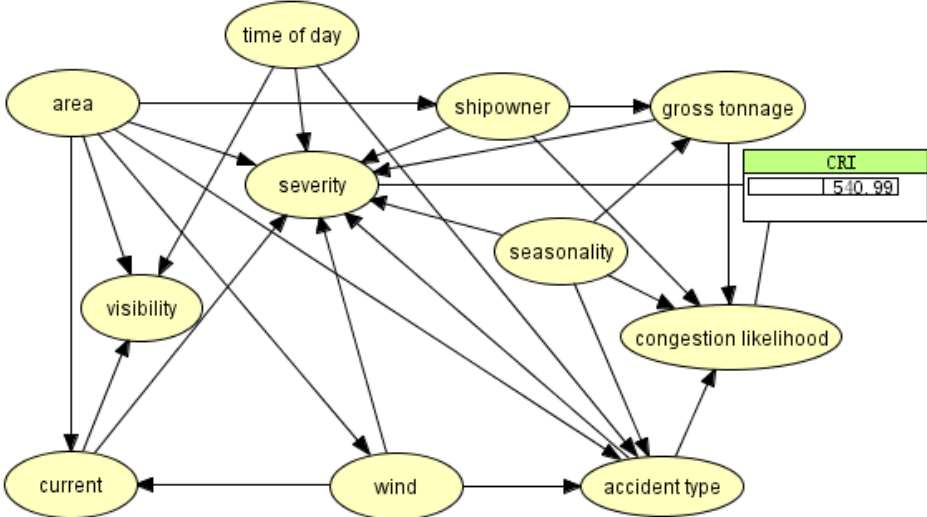


Figure 4: BN for congestion risk of the Yangtze River

Based on the BN model, congestion risk can be analyzed by the change of single SCF as well as multiple SCFs. Following an extensive analysis, it is found that both the upstream and the midstream of the Yangtze River have the relatively high risk of congestion. Grounding tends to be the most outstanding accident type influencing the congestion risk. The result also reveals that severe weather and confined channel conditions would lead to significant increase in congestion risk level, while large scaled and privately owned vessels are in need of further risk control options with respect to their high conditional CRI values.

Another superior characteristic is that the network can be updated whenever new data or knowledge is available, by simply transforming the prior into posterior probabilities by Bayes theory. The precision of model will be improved gradually with more information sources that are collected and incorporated.

4. CONCLUSION

Maritime transportation carries high potential risk, which is one of the largest concerns all over the shipping industry. Risk assessment has been widely used in both design and operation phases. Some theories and methodologies such as fuzzy logic, AHP, ER and BN are useful to deal with uncertainties, as they can synthesize objective data with subjective knowledge. Two case studies in the Yangtze River were introduced briefly to illustrate the application of several approaches introduced in maritime risk assessment. Consequently, more attention should be paid to some novel theories such as Resilience Engineering which can bring new sights to investigate maritime risk under certain uncertainties.

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