https://dx.doi.org/10.1016/j.oceaneng.2021.108622

A novel emergency decision-making model for collision accidents in the Yangtze River

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Abstract: Collision accident accounts for the largest proportion among all types of maritime accidents, emergency decision-making is essential to reduce the consequence of such accidents. This paper proposes a novel Bayesian Network based emergency decision-making model for consequence reduction of individual ship-ship collision in the Yangtze River. The kernel of this method is to propose a three-layer decision-making framework, to develop the graphical structure for describing the accident process and to establish the conditional probability tables for the quantitative relationships. The merits of the proposed method include the intuitive representation of accident development, easy to implement, ability to deal with incomplete information and updated information. This proposed method is applied to a typical collision accident in the Yangtze River. Consequently, this paper provides a practical and novel decision-making method for collision accidents.

Key words: collision accidents; decision-making; Bayesian network; maritime safety

1 Introduction

Collision accident is a frequently occurring maritime accidents in open seas (Montewka et al., 2014; Goerlandt & Kujala 2011), ports (Yip, 2008; Zhang et al., 2016), straits (Zhang et al., 2019; Ulusçu et al., 2009; Qu et al., 2011; Uğurlu et al., 2016), and inland waterways (Zhang et al., 2013; Wang et al., 2019). Specifically, in the Gulf of Finland, the collision accidents ranked second among all types of accidents from twenty years of survey. Similarly, in the port area, the collision accident occurs more frequently due to the high traffic density (Mou et al., 2010) and complexity of marine traffic (van Westrenen and Ellerbroek 2015; Wen et al., 2015). In Hong Kong Port, the collision accidents account for 54% (Yip, 2008); and in Tianjin Port, this type of accident accounts for 72.41% (Zhang et al., 2016). In the strait of Istanbul, the collision accident also ranks first in the majority of years from 2000 to 2010 (Uğurlu et al., 2016). In the Yangtze River, the collision accident account for 58.87% (Zhang et al., 2013), this also ranks first according to the high traffic density.

Owing to the nature of high occurrence and relatively serious consequence, many studies have focused on the prevention of collision accidents. These previous studies can be categorized into three types, which are collision avoidance, risk mitigation from the marine traffic perspective and risk analysis and root cause analysis perspective. The first type mainly focuses on reducing the occurrence probability of ship-ship collision (micro perspective) in the high sea. The second type focuses on reducing the occurrence probability of collision of traffic flows (macro perspective). The third type focuses on reducing both the occurrence and consequence of collision accidents using historical data (macro perspective). The comparison of the three types is shown in Table 1, in which five references are quoted for each category although many more studies can be found. Specifically, previous studies on each category are compared in Table 1.

Table 1. Comparisons of the studies on collision accidents

Categories	Collision avoidance	Risk mitigation of marine traffic	Risk analysis and root cause analysis
Collision type	Individual or multiple ship-ship collision	Collision of traffic flows	Collision of traffic flows
Perspective	Micro perspective	Macro perspective	Macro perspective
Reduction	Occurrence probability	Occurrence probability	Both occurrence probability and consequence
Data used	AIS data or simulation data	AIS data or simulation data	Historical data
Measurement method	Simulation, Linear regression, ship domain, fuzzy logic, etc	Simulation, ship domain, near miss, etc	Econometrics, Bayesian Network, data mining, etc
References	(Ozturk and Cicek 2019; Balmat et al., 2009; Bukhari et al., 2013; Goerlandt et al., 2015; Perera et al., 2011)	(Qu et al., 2011; Goerlandt & Kujala 2011; Merrick et al., 2003; Zhang et al., 2019)	(Hänninen et al., 2014; Zhang et al., 2016; Zhang et al., 2019; Kum and Sahin 2015; Yang et al., 2013)

The first type is to reduce the occurrence probability by considering the individual ship-ship and multiple ship collision avoidance. Recently, Ozturk and Cicek (2019) systematically reviewed the individual ship-ship collision risk assessment in ship navigation, and compared their difference and overlaps (i.e. navigation collision risk) between maritime transportation risk analysis and collision avoidance. 34 models associated with ship-ship collision are analysed, by comparing the aim and the measurement criteria. In this study, the maritime transportation risk analysis is considered as a special type of ship-ship collision and is regarded as the third type. Moreover, the five most used parameters for collision avoidance from previous studies are Distance to Closest Point of Approach (DCPA, 54.3%), Time to Closest Point of Approach (TCPA, 51.4%), relative bearing (37.1%), distance (34.3%), and speed (22.1%). From this analysis, it can be seen that the most widely used parameters of collision avoidance are from the individual ships, and this type of study aims to reduce the occurrence of ship-ship collisions.

The second type is to reduce the occurrence probability by considering the ship traffic flows (Chen et al., 2019). When navigating in the fairways, the traffic flow is complex owing to the typical three scenarios, which are overtaking, crossing and head-on. From previous studies, a mathematical model by using several parameters has been used to address this problem by Pedersen (1995). Moreover, the stochastic process models have been introduced to estimate geometric collision probability. Four typical waterway areas have introduced this method to estimate the collision probability, which are the Gulf of Finland (Kujala et al., 2009), in the Singapore Strait (Kang et al., 2019), in Portugal (Silveira et al., 2013), and in the San Francisco Bay (Merrick et al., 2003). From previous studies, the different collision probabilities of these three scenarios have been estimated (Otto et al., 2012; Chai et al., 2017; Goerlandt & Kujala 2011) and can be readily extended to other waterways to reduce the occurrence probability.

The third type is to reduce both the occurrence probability and consequence from a macro perspective. This type often uses historical accident data to learn lessons from the existing failure patterns. From the previous review on maritime safety (Yang et al., 2013), it can be seen that many studies focused on the risk mitigation in the framework of formal safety assessment (FSA), which includes hazard identification, risk estimation, risk control options, cost benefit analysis, and recommendations for decision-making. In practice, several quantitative methods have been proposed for such risk analysis. For example, fuzzy logic (Sii et al., 2001), evidential reasoning (Zhang et al., 2014), Bayesian Network (Fu et al., 2016), econometrics (Yip et al., 2015; Talley et al., 2012), and the combination of these methods (Yang et al., 2009; Wang et al., 2013) to address the problem of uncertainty. Moreover, the root cause analysis (Kum and Sahin, 2015) is often conducted to address the deficiencies (Yang et al., 2013) when using FSA. In risk analysis, the reduction of occurrence probability and consequence is carried out in a specific waterway and/or in a period.

From the above analysis, it can be seen that few studies focused on the consequence reduction of individual ship-ship collision. Specifically, the first type is to reduce occurrence probability but with few studies considering the consequence reduction. The second and third types focused on the risk mitigation from a macro perspective, and it cannot (1) be conducted in real-time, which is the requirement of the consequence reduction (Wu et al., 2017b; Jasionowski 2011), and (2) from an individual ship-ship collision perspective. To address the research gaps, the emergency decision-making method, which has been widely used for other types of maritime accidents (Wu et al., 2016; Krohling and Campanharo 2011), is developed in this paper. The motivation of this paper is to reduce the individual ship-ship collision consequence in real-time by considering the constraints of emergency response to maritime accidents.

The remainder of this paper is organized as follows. Section 2 analyse the statistical data of emergency response to collision accidents. Section 3 develops a decision-support approach for collision accidents in Yangtze River. Section 4 applies the proposed method to a typical scenario in the Yangtze River. Discussions are carried out in Section 5, and conclusions are drawn in Section 6.

2 Statistical data of emergency response to collision accidents

From 2013 to 2016, 942 collision incidents occurred in the Yangtze River. Two things should be mentioned about this data. First, the number of collision incidents is 963 during this period, however, considering some incidents involving the fishing boat, which is not in the charge of maritime safety administration, these incidents are excluded in this paper. Second, this paper focused on the incidents, which means the collision has been occurred but may cause minor or even no consequence. In fact, from Figure 1, it can be seen that although around 189 collision incidents occurred each year in the Yangtze River, there are fewer than 19 shipwrecks and 11 fatalities. This is because the emergency response to such incidents is relatively effective. Therefore, the experience of emergency response to such accidents should be summarised and adopted for the emergency response to potential collision accidents in the future. We need to stress that not all the collision incidents had taken effective and appropriate response actions, but from the statistical data, some incidents had not taken the best response actions and finally caused shipwreck or fatality accidents.

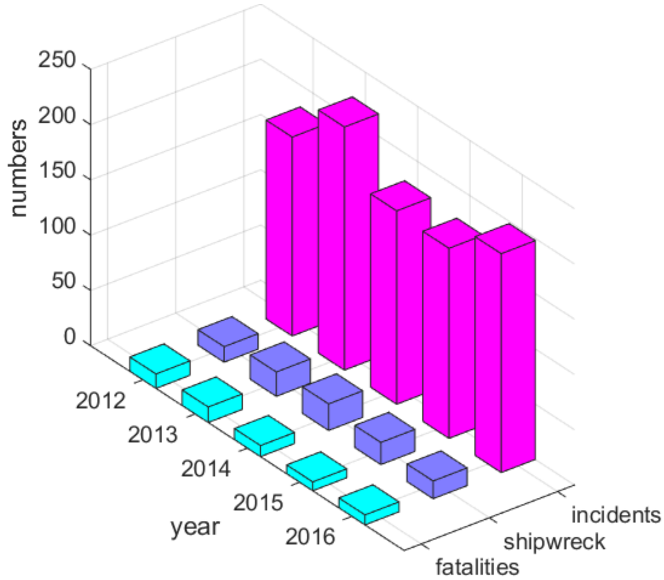

Figure 1. The numbers and severity of collision incidents in the Yangtze River

From the statistical data, there are often four options for collision accidents in the Yangtze River, which are, continue sailing (A1), beaching (A2), tug assistance (A3), and abandon ship (A4). From Figure 2, it can be seen that option A2 is the most widely used, accounting for 42% of the 942 cases, with A1 accounting for 27%, A3 accounting for 25% and A4 accounting for 5%. The detailed descriptions and explanations of these options are as follows.

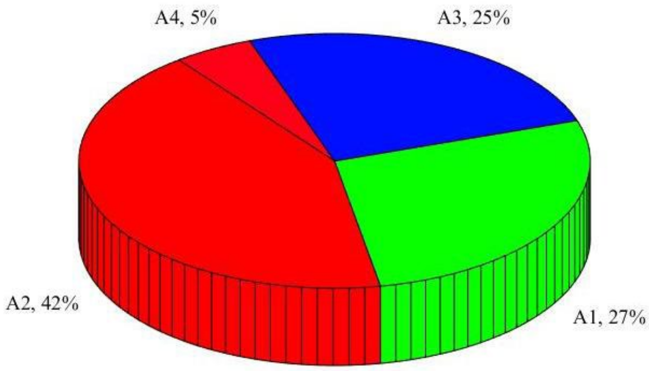

Figure 2 Response actions for collision accidents

Continue sailing (A1): The collided ship continues to navigate because the hull damage is slight and the ship can prevent flooding by leak stoppage and flooding discharge. When the ships anchoring in the nearby anchorage is also treated as this option. This is because after collision, the ships should anchor in the anchorage with a distance of around 1 nm (nautical miles) for accident investigation, and since the collided ship can navigate to the nearby anchorage, it is believed to be in good condition. In practice, if the colliding and being collided ships can well adjust the collision speed and angle, the hull damage is often not serious.

Beaching (A2): This option means the collided ships have to beach in the nearby shallow waters to avoid sink because the ship floods quickly even after taking the intervention measures (i.e. leak stoppage and flooding discharge). In the Yangtze River, the two-way channel for ship navigating is 500m width and with another special lane for the small-sized ship with draught less than 7.0m. If the ship cannot prevent the flooding effectively, the most widely used method is to beach the ship initiatively. By taking this option, although the collided ship has a risk of bottom damage, it can be avoided from sinking. In practice, this option should be carefully handled owing to the following two reasons. First, in the Yangtze River, there are many wharfs, bridges and anchorages, the collided ships should avoid to collide with such infrastructures and nearby ships. Second, the shallow waters should be suitable for beaching. For example, if the sediment of such shallow water is hard, the ship bottom may be seriously damaged. Another example is that if the ship cannot be totally grounded (i.e. only small part on the shallow waters), the ship may have the risk of capsizing when the water levels fluctuate (Wu et al., 2017a) or the wind changes to strong. Moreover, when taking this option, the colliding ship should try to push the collided ship to the shallow water with dead slow ahead.

Tug assistance (A3): The collided ship is anchored or moored with the help of a tug. If a collided ship is anchored with the help of a tug, this scenario is treated as tug assistance rather than continue sailing (A1).

Abandon ship (A4): The crews have no choice but to abandon the ship. Note this is always the last choice, this can also be discovered from the statistical data.

3 Proposed decision-support approach for collision accidents in the Yangtze River

3.1 Developing the three-layer framework for collision accidents

Similar with the previous studies (Wu et al., 2017a; Wu et al., 2018a), the generic three-layer framework using Bayesian Network (BN) for emergency decision making of collision accidents can be established. Take the beaching option as an example, the developed three-layer framework is shown in Figure 3. Note that the influencing factors are incomplete in this figure. Specifically, the first layer is the influencing factors, in practice, they can be derived from the expert judgements or from the historical data (Hänninen et al., 2014; Fu et al., 2016; Wu et al., 2017b). The second layer is the evaluation factors, these factors are introduced to facilitate the understanding on the influencing mechanism of the influencing factors, note that one evaluation factor could be the parent node of another evaluation factor, and this can be seen from Figure 3 that the condition for slope is the parent node of the condition for beaching. The last layer is the response options for collision accidents. In practice, by introducing this framework, the decision-maker only has to know the prior information of the influencing factors in the first layer, and the optimum option for emergency response to such collision accident can be derived.

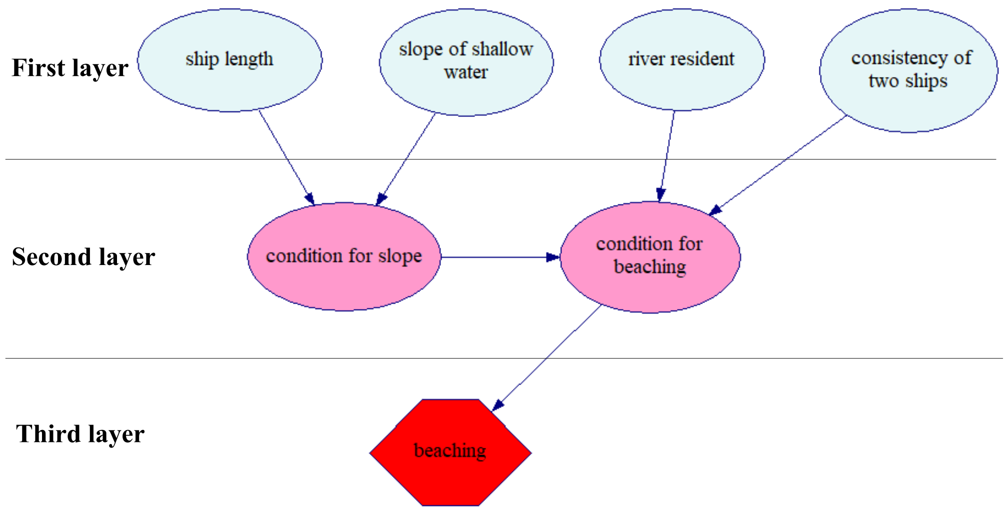

Figure 3. Generic three-layer framework for emergency decision-making of collisions accidents

By introducing the generic three-layer framework, the flowchart of developing the BN based emergency decision-making model is shown in Figure 4. The detailed three steps are as follows.

The first step is to establish a graphical structure for the BN based model. In this step, previous studies and historical data are used to identify the influencing factors and evaluation factors. After identifying the factors, the complete graphical structure of the BN can be derived by introducing the generic three-layer framework.

The second step is to derive the conditional probability tables (CPTs) to establish the quantitative part of the BN. As some evaluation factors have been recorded in the database, the CPTs can be derived directly from the historical data. However, some evaluation factors are used for facilitating the modelling process, and the corresponding CPTs are derived by using the extended IF-THEN scheme.

The last step is to inference the posterior probability by introducing the prior information of the collision accident, and finally, the optimum option can be selected by introducing the utility value nodes.

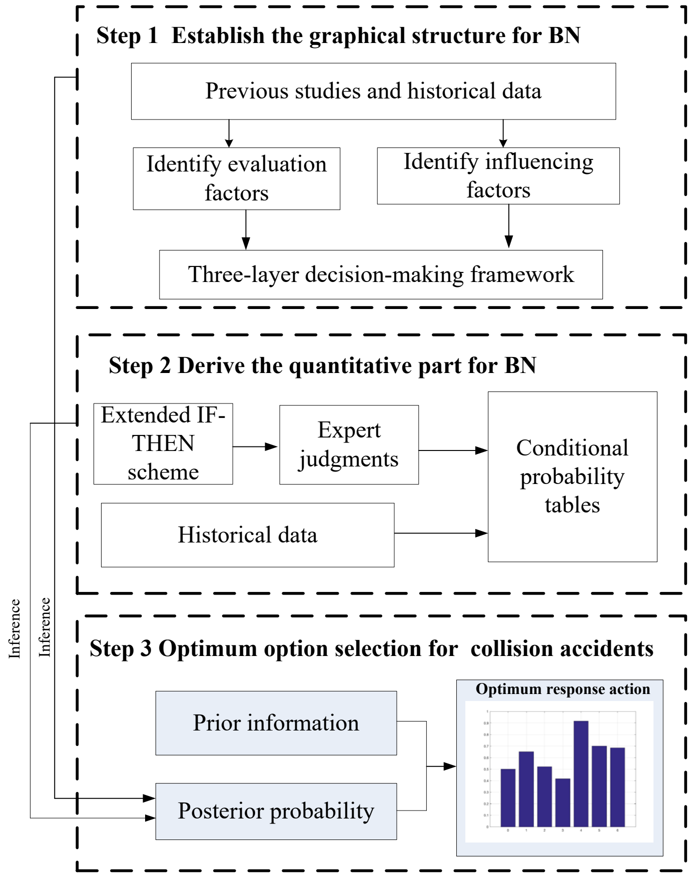

Figure 4 Flowchart of developing BN based decision-making model

3.2 Identifying the influencing factors for the emergency decision-making

The identification of influencing factors is a significant step for emergency decision-making of collision accidents, which is also the first step in the decision-making modelling process. In order to achieve a comprehensive evaluation on the ship condition and navigation situation, majority of these factors are identified from previous studies, and the references or reasons of choosing these factors are summarised as shown in Table 1.

It should be noted that some influencing factors are unique for emergency decision-making of collision accidents, which are dead slow ahead to prevent the separation of ships, slope of shallow waters, consistency of two ships, and minimum freeboard. The detailed explanations of choosing these factors are as follows:

(1) Dead slow ahead to prevent the separation of ships. The dead slow ahead is a good seamanship when handling the colliding ships, which can be used to prevent the two ships from being separated. In a previous study (Montewka et al., 2014), this has also been considered. The reason is that once if the ship is damaged and the colliding ship quickly pulls out from the collided ship, the flooding speed will be accelerated. Therefore, the ship should try to push the collided ships until the flooding protection has been successfully carried out. However, note that the ship speed should not be high, that's because too high speed may aggravate the damage of the collided ship. Therefore, dead slow ahead which can prevent the two ship being separated is an effective method and should be considered when selecting the best option for emergency response to collision accidents.

(2) Slope of shallow waters. When the collided ship initiatively grounds on the shallow waters, the conditions of the shallow water must be considered. As from the previous study (Wu et al., 2017a), the river sediment is a significant factor to judge whether the bottom of ships will be damaged or not. Another significant factor is the slope of the shallow water, this is because the ship should be totally grounded in the shallow waters and with the rudder and paddle not seriously damaged. Hence, the appropriate slope will easy to manoeuvre the collided ship being grounded in good condition. From the

working experience of the captions, the slope is a significant factor for this manoeuvring.

(3) Consistency of two ships. The consistency of two ships means that the colliding and collided ships can move consistently, i.e., the two ships can move ahead or astern together with good coordination. This is important to judge whether the colliding ship can push the collided ship to the shallow waters. If the consistency of two ships is low, the collided ship has to move to the shallow waters by herself, which is very hard since the collided ship has been damaged.

(4) Minimum freeboard. The minimum freeboard is the index to judge whether the ship can float or not. Since the collided ship has been damaged, the ship buoyancy will be decreased. If the ship has been damaged seriously and flooding quickly, the freeboard may not meet the safety requirements of ship buoyancy. In practice, this minimum freeboard is defined as 76mm.

Table 1. Influencing factors for emergency decision-making of collision accidents

Influencing factors	References
Wind speed (Beaufort scale)	(Wu et al., 2015; Balmat et al., 2011)
Current (kn)	(Zhang et al., 2013; Zhang et al., 2016)
Dead slow ahead to prevent the separation of ships	(Montewka et al., 2014)
Dead weight tonnage (DWT)	(Wu et al., 2017a; Sormunen et al., 2015)
Collision angle (°)	(Montewka et al., 2014; Sormunen et al., 2015)
Collision part of ship	(Montewka et al., 2014; Wu et al., 2017a)
Ship length (m)	(Balmat et al., 2011; Wu et al., 2016)
Collision speed (kn)	(Montewka et al., 2014; Sormunen et al., 2015)
Arrival time of tug (min)	(Wu et al., 2017; Shi et al., 2014)

Slope of shallow waters	From ship manoeuvring experience
River sediment	(Wu et al., 2017a)
Consistency of two ships	From ship manoeuvring experience
Minimum freeboard (mm)	From the requirement of ship safety

3.3 Establishing the graphical structure for collision accidents

After identifying the influencing factors, the states of these factors should be derived to develop the first layer of the BN based decision-making model. Note that when defining the states of the influencing factors, the number of the states should be carefully handled. If there are too many states, too many CPTs should be developed, which makes it impossible in practice. For example, if there are three parent nodes and each with five states, 125 (i.e. $5\times5\times5=125$) conditional probabilities should be established (Yang et al., 2008; Wan et al., 2019). However, if there are only a few states (e.g. two states), it will be difficult to distinguish the difference among the states, since some of the descriptions of the influencing factors are ambiguous or fuzziness. Therefore, three states are used for describing the influencing factors, and their explanations are shown in Table 2.

Table 2 States of the influencing factors and their explanations

Nodes	States	Explanations
Wind speed (Beaufort scale)	Less than 3/ from 3 to 6/ more than 6	The leak stoppage will be easy if the wind speed is low, otherwise, it is hard to conduct leak stoppage.
Current (kn)	Less than 1/ from 1 to 3/ more than 3	The current will make both colliding and being collided ships adrift, which will influence the leak stoppage.
Dead slow ahead to prevent the ships separation	Feasible/ unfeasible	Using dead slow ahead of the colliding ship is good seamanship to prevent separation of two ships and the flooding speed will be reduced by using this operation.

DWT of colliding ship	Less than 10,000/ from 10,000 to 30,000/ more than 30,000	The large-sized ships will have relatively larger collision mass than small-sized ships.
Collision angle (°)	Less than 15/ from 15 to 75/ from 75 to 90	The right collision angle will cause large collision mass.
Collision part of ship	Stem/amidships/stern	The collision on the ship amidships should be avoided, and the collision on the stern will have a large likelihood of mechanical damage (i.e. rudder and paddle).
Ship length (m)	Less than 100 /from 100 to 200/more than 200	The large-sized ship has better discharge ability of inflow than small-sized ships.
Collision speed (kn)	Less than 2/from 2 to 6/ more than 6	The high speed will cause large collision mass.
Arrival time of tug (min)	Less than 15/30/45	The arrival time of the tug is significant in the emergency response owing to the time limitation.
Slope of shallow waters	Less than 15/ from 15 to 18/ from 18 to 24	Ships will be easy for beaching with appropriate slope conditions.
River sediment	Soft/hard	Hard river sediment has a higher likelihood of causing damage to the beaching ships than the soft sediment.
Consistency of two ships	Consistency/ inconsistency	If the two ships cannot move with consistency, it is hard to push the collided ship for beaching.
Minimum freeboard (mm)	Less / more than 76	The freeboard is an index to determine whether this ship can be safe afloat or not.

In order to facilitate the modelling process, the evaluation variables are introduced. Specifically, they can be derived from previous studies, which are the natural environment (Zhang et al., 2016; Wu et al., 2016), leak stoppage (Wu et al., 2017a), flooding water (Montewka et al., 2014; Jasionowski et al., 2011), damage extent significant (Montewka et al., 2014); hull damage (Prestileo et al., 2013; Gledić et al., 2019), mechanical damage (Montewka et al., 2014; Wu et al., 2017a), discharge ability (Santos and Guedes Soares 2009), actual flooding water (Wu et al., 2017a), condition for beaching (Wu et al., 2017a). Note that the condition for slope is introduced in this paper since the slope is important for the beaching conditions from the working experience. The summary of the evaluation variables in this decision-making based model is shown in Table 3.

Table 3. States of the evaluation variables and their explanations

Nodes	States	Explanations
Natural environment	Good/normal/bad	The condition of natural environment is important for leak stoppage.
Leak stoppage	Easy/normal/difficult	The leak stoppage is easy or difficult to conduct.
Flooding water	Quickly/moderately/slowly	The ship flooding speed is quickly/moderately/slowly.
Damage extent significant	Significant/moderate/ insignificant	The extent to cause damage is significant or not.
Hull damage	Seriously/moderately/slightly	The ship hull is seriously/ moderately/ slightly damaged.
Mechanical damage	Damaged/undamaged	The rudder or paddle is damaged or undamaged.
Discharge ability	Good/normal	The ship discharge ability of inflow is good/bad.
Actual flooding water	Quickly/moderately/slowly	The ship flooding speed is quick/moderate/slow after taking the response actions.
Condition for slope	Good/bad	The slope of the shallow waters is good or bad for beaching.
Condition for beaching	Good/normal/bad	The condition is good/normal/bad for beaching.

After defining the influencing factors and the corresponding states, the three-layer emergency decision-making model for collision accidents can be derived, which is shown in Figure 5.

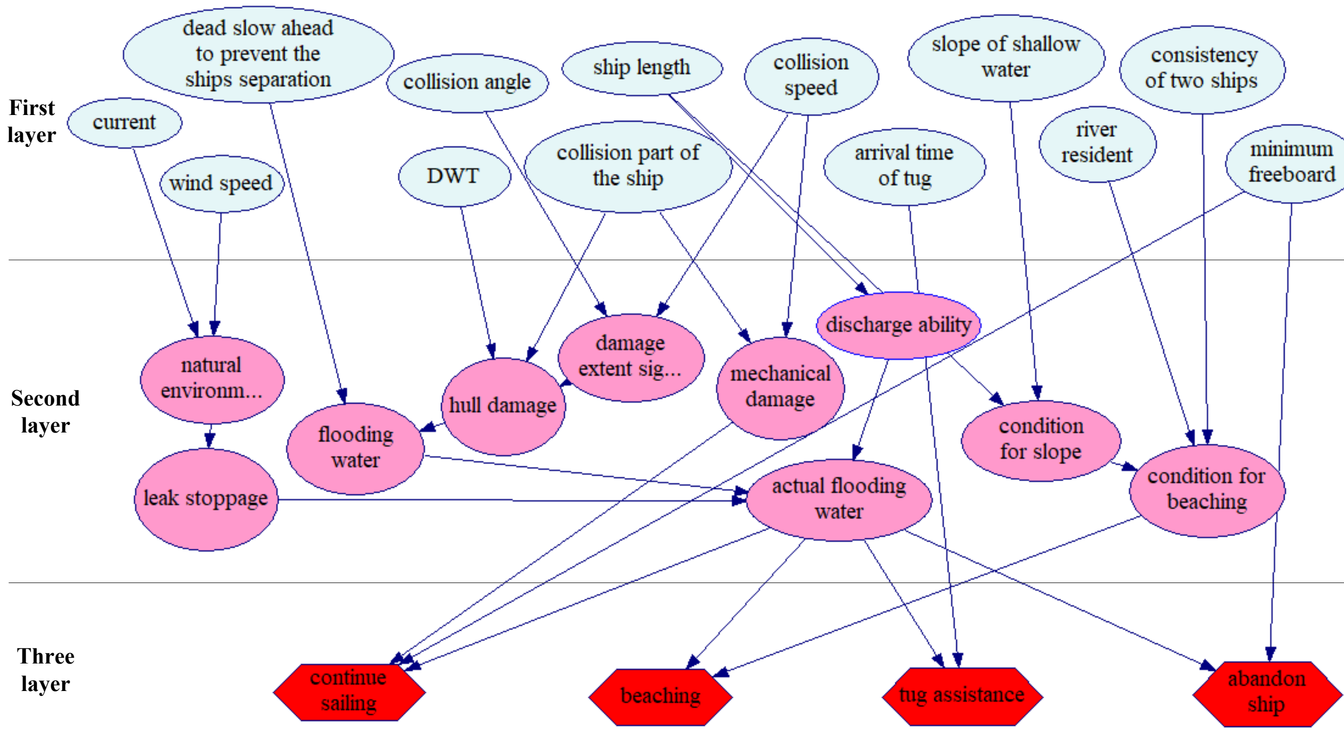

Figure 5. Graphical structure of emergency decision-making model for collision accidents

3.4 Use of the extended IF–THEN rules to derive the CPTs

After establishing the graphical structure, another essential step is to derive the CPTs for the BN based decision-making model. The most common and easy way to derive the CPT is by using historical data or from the previous studies. For example, the damage significant extent, which has been used for the collision risk analysis by Montewka et al. (2014), the CPT can be easily derived from their study though the two studies have some slight differences, and the established CPT is shown in Table 3. From this table, it can be seen that if the ship collides another ship with a close to the right angle and with a high speed, this collision will be believed to be damage extent significant. Moreover, if the ship collides another ship with a small angle, this collision will be believed not to be damage extent significant.

Table 3. CPT for damage extent significant

Collision angle	Less than 15			From 15 to 75			From 75 to 90		
Collision speed	Less than 2	From 2 to 6	More than 6	Less than 2	From 2 to 6	More than 6	Less than 2	From 2 to 6	More than 6
Significant	0	0.2	0.3	0.2	0.3	0.6	0.5	0.7	0.95
Moderate	0.1	0.6	0.6	0.5	0.5	0.3	0.4	0.3	0.05
Insignificant	0.9	0.2	0.1	0.3	0.2	0.1	0.1	0	0

However, although more than 900 collision accidents have occurred in the Yangtze River, it is also hard to establish the CPTs for all the evaluation variables owing to the two following reasons. First, some evaluation variables are introduced to facilitate the modelling process by reducing the number of CPTs and better understanding on the accident development process. Therefore, these evaluation variables did not have any records in the historical data, which makes them hard to directly derive from the historical data. Second, although the majority of collision accidents have taken effective response actions, which can be seen from the Figure 1 that few fatalities and shipwrecks have been caused, some collision accidents have not been well treated and the response actions should be improved.

In order to address this problem, the extended IF-THEN scheme, which has been widely used for the decision support (Yang et al., 2008; Liu et al., 2013), is introduced in this paper to derive the CPTs for the evaluation variables. Before using the extended IF-THEN rules, the traditional IF-THEN rules, which is used in the fuzzy logic based method (Zhou et al., 2018; Kuzu et al., 2019), should be described for comparison. Take the evaluation variable of condition for slope as example, the traditional IF-THEN rules can be established as: **If the ship length is *less than 100m* and the slope of shallow waters is *less than 15*, then the condition for slope is *good*.**

However, it can be seen that this traditional IF-THEN rule cannot accurately describe the output variable (i.e. condition for slope). In practice, it is hard to judge that the slope is 100% good or bad. Therefore, the belief degree is introduced, and the extended IF-THEN rules can be established as: **If the ship length is *less than 100m* and the slope of shallow waters is *less than 15*, then the condition for slope is *good* with a belief degree of 0.9, and is *bad* with a belief degree of 0.1.**

By introducing this extended IF-THEN rules, the CPTs for the evaluation variables can be obtained. Four experts are invited for the judgment to derive the CPT, and the detailed information is as follows. A professor, from university, and he has been worked as chief officer on the ocean-going ships. An officer, from the maritime safety administration, and he has successfully handled more than 100 collision accidents in the Jiangsu Section. A tug captain, from the Nanjin Port Tug and Lighter Company, and he has often requested for tug assistance for maritime accidents. A captain, from the ocean-going ship, and he has worked more than 20 years in the Nanjin Tanker Corporation. The four experts are invited to make judgments on each rule and the average value is used for the CPTs.

Since the condition for beaching is a popular response option to collision accidents, the CPTs for two associated nodes (a condition for slope and condition for beaching) are given in this paper.

Table 4. CPT for condition for slope

Ship length (m)	Less than 100			From 100 to 200			More than 200		
Slope of shallow water	Less than 15	From 15 to 18	From 18 to 24	Less than 15	From 15 to 18	From 18 to 24	Less than 15	From 15 to 18	From 18 to 24
Good	0.9	0.4	0.2	0.3	0.9	0.3	0.2	0.4	0.9
Bad	0.1	0.6	0.8	0.7	0.1	0.7	0.8	0.6	0.1

As shown in Table 4, it can be seen that when the ship length is less than 100m, it is better to beach the ship on the shallow waters with a slope of 15. If the ship length is from 100m to 200m, the appropriate slope of shallow waters for such beaching is from 15 to 18. If the ship length is more than 200m, the appropriate slope of shallow waters for such beaching is from 18 to 24. Moreover, by introducing the extended IF-THEN rules, it can well describe whether the slope of shallow waters is good or bad for beaching. For example, when the ship length is from 100m to 200m and the slope of shallow water is less than 15, it can be seen that the condition for slope is good with a belief degree of 0.3 and is bad with a belief degree of 0.7. From this result, it can be seen that the condition for slope is relatively bad but it is not 100% bad, which reflects the advantages of IF-THEN rules when describing the consequent.

Similarly, the CPT of condition for beaching can also be derived and the results are shown in Table 5. From this table, it can be seen that only 24 (i.e. $2 \times 2 \times 2 \times 3 = 24$) combinations need to be judged. However, if the condition for slope is not introduced, there will be 108 (i.e. $3 \times 3 \times 2 \times 2 \times 3 = 108$) combinations that need to be judged by the experts, which is challenging in practice. Moreover, by introducing the condition for slope, it is easy to understand how the condition for slope is being influenced by the ship length and slope of shallow waters, and also how the condition for beaching is being influenced by the river resident, consistency of two ships and condition for slope. Note that the consistency of the river resident is another key factor to judge whether this shallow waters can be used for beaching or not. Specifically, if the two ships cannot move consistently or the river resident is hard, this shallow water is believed to be NOT good, and this can be seen from the CPT of the condition for beaching.

Table 5. CPT for condition for beaching

River resident	Soft				Hard			
Consistency of two ships	Yes		No		Yes		No	
Condition for slope	Good	Bad	Good	Bad	Good	Bad	Good	Bad
Good	0.95	0.2	0.2	0.1	0.2	0.1	0.1	0.05
Normal	0.05	0.5	0.5	0.5	0.5	0.5	0.5	0.2
Bad	0.00	0.3	0.3	0.4	0.3	0.4	0.4	0.75

3.5 Introducing utility value for response options selection

The final decision-making is carried out by introducing the utility value, the quantitative relationship between the evaluation variables and the response actions are also derived by using the IF-THEN rules. Take the beaching action as example, the established CPT for beaching is shown in Table 6. It can be seen from this table that if the condition for beaching is favourable, the beaching option can be taken. However, if the condition for beaching is not favourable, it is difficult for a ship to take this option in practice.

Table 6. CPT for beaching

Condition for beaching	Good		
Actual flooding water	Quickly	Moderately	Slowly
Beaching	0.7	0.8	0.95
Condition for beaching	Normal		
Beaching	0.45	0.65	0.9
Condition for beaching	Bad		

Beaching	0.2	0.3	0.35

Similarly, the CPT for other options (i.e. continue sailing, tug assistance and abandon ship) can also be derived. For the sake of space, these CPTs are not given but only some principles that can be discovered from the CPT tables are given. The conditions for continue sailing is very rigorous, and it can only be taken when the mechanical damage is undamaged, the actual flooding water is not quick and the minimum freeboard is more than 76 mm. This is owing to the following three reasons: (1) If the mechanical damage is damaged, the ship cannot use its rudder and paddle; (2) If the actual flooding water is quickly, the ship will suddenly be filled with flooding water and the stability will quickly decreased, which may cause the ship capsizing; (3) If the minimum freeboard is less than 76 mm, the ship cannot safely float on the water. The tug assistance option cannot be taken when the tug cannot arrive in a relatively short time and the flooding water is quickly. The last choice for the response actions to collision accidents is to abandon the ship if there is no other better choices can be taken.

4 Case study of decision support for collision accidents in Yangtze River

4.1 Scenario description of collision accident

On 7 March 2013, a collision accident occurred close to the No. 65 Buoy in the downstream of Yangtze River. The two ships were Jinzeng 18 and Kaihangxing 19. Both ships were inbound, and 35 crew members in total were on board. The wind speed was around 5 (Beaufort scale). The accidents caused the forepeak flooding of Jinzeng 18, finally this ship beached on the shallow water close to No. 66 Buoy. The detailed information of this collision accident is shown in Table 7. Note that the information is derived from the database in the Jiangsu Maritime Safety Administration.

Table 7. Detailed information of the collision accident in the Yangtze River

Influencing factors	Information	Influencing factors	Information
Wind speed (Beaufort scale)	5	Collision speed of colliding ship (kn)	4
Current (kn)	2.5	Arrival time of tug (min)	Less than 30
DWT of colliding ship	16,126	Slope of shallow water	16
Collision angle (°)	30	River resident	Soft
Dead slow ahead to prevent separation	Feasible	Consistency of two ships	Consistency
Collision part of the ship	Stem	Minimum freeboard (mm)	More than 76
Length of collided ship (m)	147		

4.2 Derivation of the state values of the evaluation variables

After obtaining the prior information in Table 7, it is easy to derive the state values of the evaluation variables of the emergency decision-making model for collision accidents. By using the GeNIe software, it is easy to achieve this by "*setting evidence*" on the input variables. For example, as the node of "*dead slow ahead to prevent the ships separation*" is "*feasible*", the decision-maker only have to select "*set evidence*" on the "*feasible*" state. After setting the evidence on all the input variables, the result can be derived as shown in Figure 6.

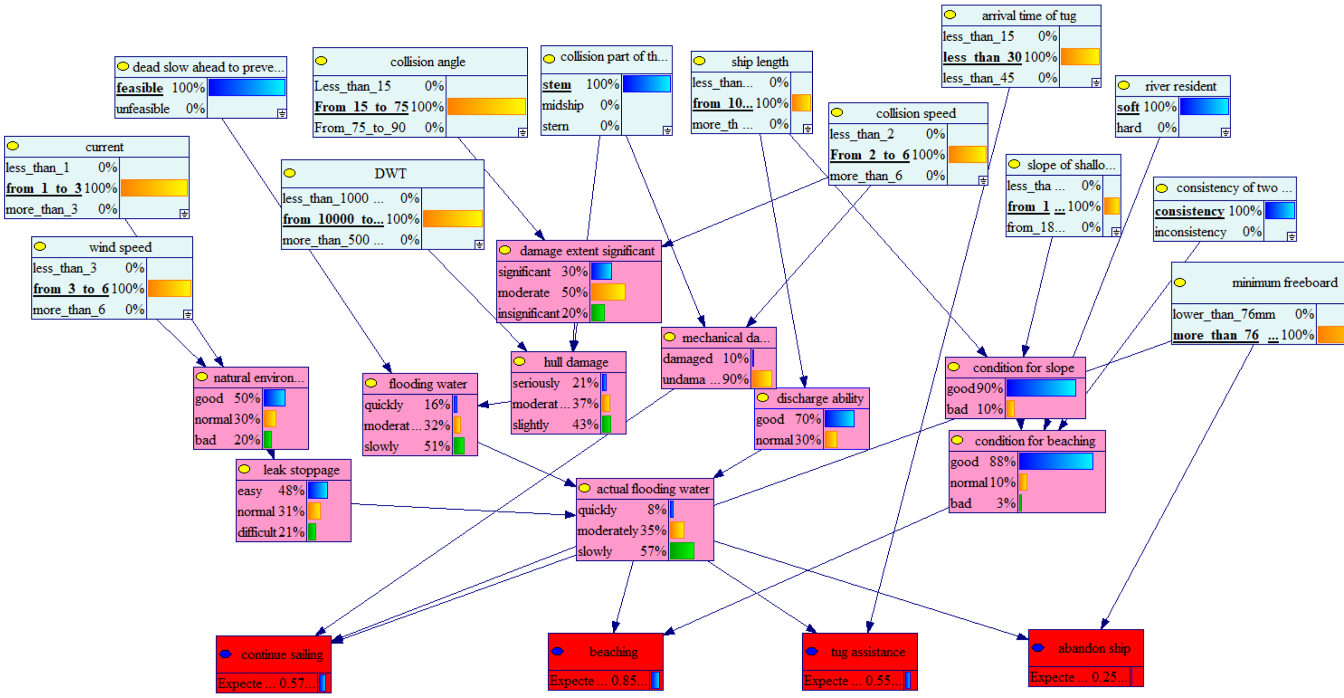

Figure 6. Results of the Bayesian Network based decision-making model

The state values of the evaluation variables can be derived, and the results are shown in Table 8. From this table, it can be seen that the natural environment is good with a belief degree of 0.50, is normal with a belief degree of 0.30 and is bad with a belief degree of 0.20. This is because both the wind speed and the current speed were moderate, which makes the natural environment not very good but acceptable for the leak stoppage. The mechanical damage was undamaged with a belief degree of 0.90 and was damaged with a belief degree of 0.10, this is because the collision part was in the stem. From the accident development, these two ships were not damaged with their rudders and paddles. As both the collision speed and collision angle are moderate, the hull damage is serious with a belief degree of 0.30; is moderate with a belief degree of 0.50; and is slight with a belief degree of 0.20. This agrees with the accident information, only the Jinzeng 18 ship was damaged with a hole in the forepeak. After leak stoppage, the actual flooding water is seriously with a belief degree of 0.08, is moderately with a belief degree of 0.35 and is slightly with a belief degree of 0.57. Another thing should be mentioned is the state values of evaluation variables related to the beaching. As the slope of the shallow water is suitable for the collided ship, it is good with a belief degree of 0.90 and is bad with a belief degree of 0.10 after inference. Moreover, the condition for beaching is also good in this scenario, which is good with a belief degree of 0.88, is normal with a belief degree of 0.10 and is bad with a belief degree of 0.03.

Table 8. State value of the evaluation variables for collision accident

Node	State 1	State 2	State 3
Natural environment	Good 0.50	Normal 0.30	Bad 0.20
Leak stoppage	Easy 0.48	Normal 0.31	Difficult 0.21
Flooding water	Quickly 0.16	Moderately 0.32	slowly 0.51
Damage extent significant	Significant 0.30	Moderate 0.50	insignificant 0.20
Hull damage	Seriously 0.21	Moderately 0.37	Slightly 0.43
Mechanical damage	Damaged 0.10	Undamaged 0.90	- -
Discharge ability	Good 0.70	Normal 0.30	- -
Actual flooding water	Quickly 0.08	Moderately 0.35	slowly 0.57
Condition for slope	Good 0.90	Bad 0.10	- -
Condition for beaching	Good 0.88	Normal 0.10	Bad 0.03

4.3 Acquisition of the best response action for collision accident

The final decisions can be made by deriving the utility value of each option, which is shown in Figure 6, and the comparison among four response actions are shown in Table 9. From this table, it can be seen that the best option is beaching in this scenario, and the continuous sailing ranks second, while the tug assistance and abandon ship rank third and fourth, respectively.

Table 9 Final decision-making for the options

Options	Abbreviation	Utility	Ranking
Continue sailing	A1	0.579	2
Beaching	A2	0.852	1
Tug assistance	A3	0.556	3
Abandon ship	A4	0.251	4

The result is reasonable because the collided ship finally beached on the shallow water close to No.66 Buoy. In fact, the beaching is taken because the ship flooding is not "seriously", therefore, the ship will not have a large probability to capsize. Moreover, the condition for beaching is good, which can be seen from Table 8 that the condition for beaching is good with a belief degree of 0.88, therefore, the ship can beach on the shallow waters to avoid influencing the passing by ships since this waterway is very busy.

Continuing to sail is another feasible option in this scenario. When a ship is not seriously damaged and her rudder and propeller are not damaged, the ship can navigate along its own proposition with good conditions or with some damage in the forepeak. Since beaching on the shallow waters is better than continuing to sail in this scenario, this option is not selected in practice.

Tug assistance ranks third because the tug can only arrive in around 30 minutes. However, as the collided ships should take response actions in a quite limited time, which makes this option only rank third. If the arrival time can be reduced to 15 minutes

(This can be easily implemented by changing the state value of arrival time of tug), the utility value will be changed from 0.556 to 0.748 and this option will be ranked second. This is because without the help of tug, the damaged ship may have some limitation in manoeuvrability and the risk of maritime accidents may increase during the continue sailing process.

Abandon ship is often the last choice when response options are considered. In this scenario, this option ranks fourth because there are other better choices. As stated before, this option can only be taken when the ship is flooding quickly after taking leak stoppage and the collided ship cannot beach on the shallow waters. In fact, when setting evidence on the actual flooding water as "quickly" and the condition for beaching as "bad", the utility value of abandon ship will be changed to 0.40, while the utility values for other options will be reduced, which makes this option have to be taken.

4.4 Decision-making for collision accident considering uncertainty

As the emergency decision-making is limited in time, the decision-maker (i.e. captain) may not collect the complete information (i.e. 100%), which includes uncertainty (e.g. 10%). For example, the captain may have 10% belief degree (doubt) on the dead slow ahead to prevent ships separation is unfeasible, which can be described by the dead slow ahead to prevent ships separation is feasible with a belief degree of 0.90 and is unfeasible with a belief degree of 0.10. In this case, the developed model can also be used for decision-making. To illustrate this decision-making process, several state values of influencing factors have been changed to the information with uncertainty. The detailed original and changed information are shown in Table 10.

Table 10. Incomplete information for decision-making of collision accident

Influencing factors	Original information	Changed information
Wind speed (Beaufort scale)	(From 3 to 6, 1.00)	(Less than 3, 0.10; from 3 to 6, 0.80; more than 6, 0.10)
Current (kn)	(From 1 to 3, 1.00)	(Less than 1, 0.10; from 1 to 3, 0.80; more than 3, 0.10)
DWT of colliding ship	(From 10000 to 20000, 1.00)	Unchanged
Collision angle (°)	(From 15 to 75, 1.00)	Unchanged
Dead slow ahead to prevent separation	(Feasible, 1.00)	(Feasible, 0.90; unfeasible, 0.10)
Collision part of the ship	(stem, 1.00)	Unchanged
Ship length (m)	(From 100 to 200, 1.00)	Unchanged
Collision speed of colliding ship (kn)	(From 2 to 6, 1.00)	Unchanged
Arrival time of tug (min)	(Less than 30, 1.00)	(Less than 15, 0.15; less than 30, 0.70; less than 45, 0.15)
Slope of shallow water	(From 15 to 18, 1.00)	(Less than 15, 0.10; from 15 to 18, 0.80; from 18 to 24, 0.10)
River resident	(Soft, 1.00)	(Soft, 0.80; hard, 0.20)
Consistency of two ships	(Consistency, 1.00)	(Consistency, 0.80; inconsistency, 0.20)
Minimum freeboard (mm)	(More than 76, 1.00)	(Less than 76, 0.30; more than 76, 0.70)

By using the changed information, it can be seen that the utility values for four response actions are changing. The beaching option is changed from 0.85 to 0.74, which has reduced a lot because the condition for beaching has been changed to be a little bad. The tug assistance ranked second under this new scenario though the utility value has only reduced by 0.02. This is because the utility value of continue sailing has reduced a lot (i.e. from 0.57 to 0.45). For further analysis, the minimum freeboard has changed with 30% uncertainty, which makes it is hard to judge whether this ship can safely navigate with the forepeak damaged.

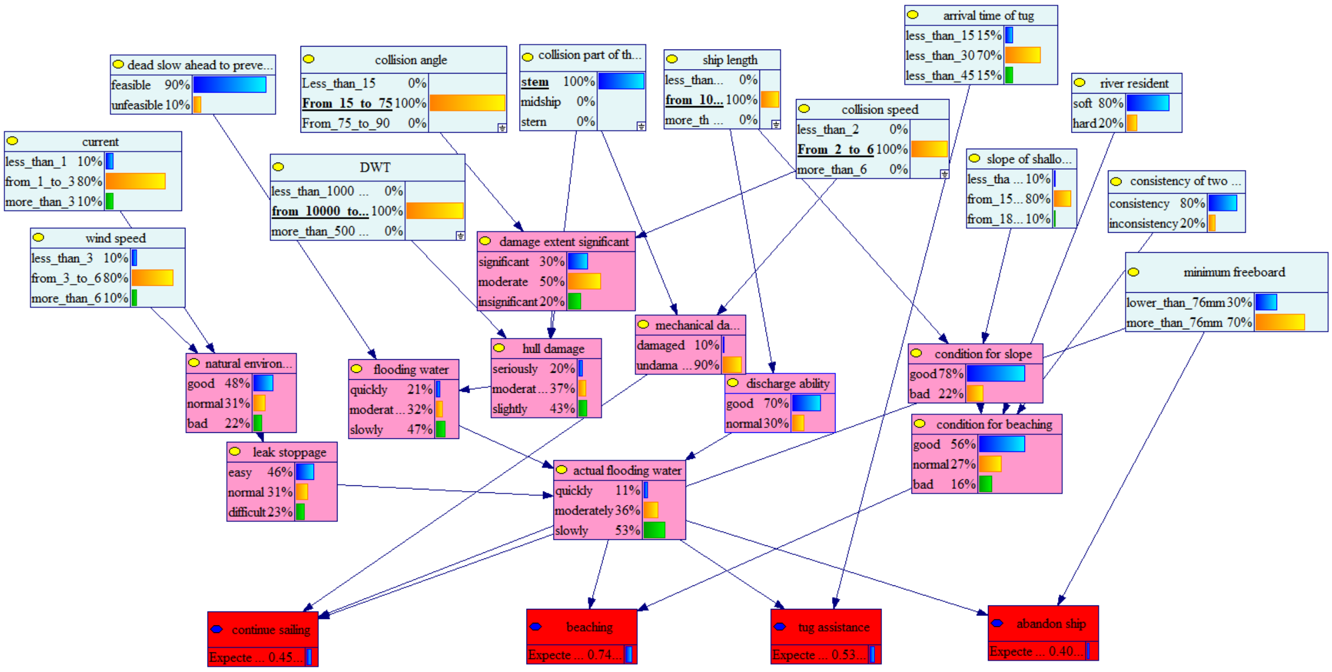

Figure 7 Bayesian Network based decision-making model under uncertainty

Another merit of the Bayesian Network based decision-making model is that it can also change the values of the evaluation variables. For example, after inference, the hull damage is seriously with a belief degree of 0.21, is moderately with a belief degree of 0.37 and is slightly with a belief degree of 0.43, which can be seen in Figure 6. In practice, if the captain discovers that the hull is seriously or slightly damaged, the captain can directly change this state value by ignoring the inference result that considering the DWT and other factors. In order to illustrate this, an example is used in this section. The detailed information is as follows: (1) The mechanical damage is undamaged; (2) Hull damage is moderate; (3) The condition for slope is good with a belief degree of 0.89 and is bad with a belief degree of 0.11. The result has been changed and shown in Figure 8. By changing these values, it can be seen that the utility value of beaching is 0.78, which has been increased and it means that the captain should be confident to select this response option. Therefore, this merit will make the proposed model especially useful if there are two options with approximately equal utility value, and the updated information can provide a practical tool to help the captain to make decisions.

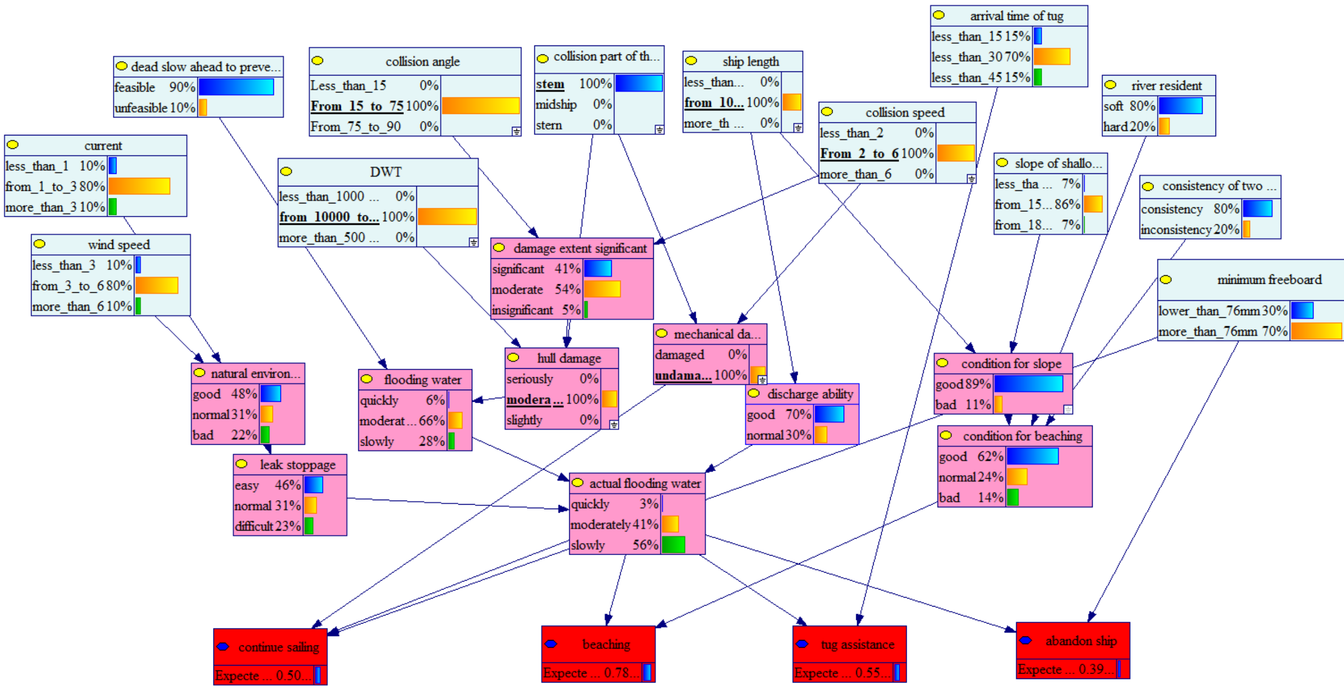

Figure 8. Bayesian Network based decision-making model with updated information

5 Discussion

In this paper, the expert judgements are used to derive the CPTs. This is quite different from the data-driven decision-making model, which only uses historical data to quantify the influencing factors (Wu et al., 2016). Two reasons for using expert judgements are as follows. First, the collision accident is different from the not under control incident. The collision may cause some fatalities and shipwrecks from the historical data, while the not under control incident has caused few fatalities. This means some of the collision accidents have not been well handled and improvement are needed in this response process. Therefore, the historical data, which includes some data that has caused fatalities, should be not considered. Second, introducing expert judgements can have a well understanding on the accident development process. Moreover, if the decision-maker has new information on the evaluation variables, it is easy for him to directly update the information on the evaluation variables, which has been illustrated in Subsection 4.4 and it is especially useful when the utility values of two or more options are approximately equal.

When developing the three-layer decision-making model for the collision accidents, the historical data is used to derive the four options (i.e. continuing to sail, beaching, tug assistance and abandon ship). Moreover, from the statistical data, the beaching option is the most popular option for emergency response to maritime accidents. This is owing to the distinguishing characteristics of the Yangtze River. Specifically, there are a large amount of shallow waters along the Yangtze River, and if the condition for the shallow waters (e.g. slope and river resident) is suitable for beaching, the majority of ships upon a collision will take this option. However, this might be quite different in the high sea because there will not be suitable shallow waters available for beaching, and if the on-board flooding cannot be effectively prevented, the captain will have to abandon ship.

6 Concluding Remarks

The main contribution of this paper is to propose a novel emergency decision-making model for collision accidents. When developing this three-layer decision-making model, the BN method is introduced by developing the graphical structure and CPTs to represent the qualitative and quantitative relationships. For further analysis, the proposed BN based emergency decision-making model has several strengths. (a) It is intuitive to describe the relationships among the factors in the three-layer framework, which can help the decision-maker have a well understanding on the accident development process of collision accidents. (b) It is easy to make decisions because the decision-maker only have collected the prior information of the influencing factors. (c) It is able to deal with uncertain information of the prior information, which is very useful as the collected information may be incomplete owing to the time limitation in emergency. (d) It is able to update the new information including both the influencing factors and evaluation variables, this is useful since the initial collected data may be incomplete and the utility values of two options may be approximately equal, which makes the decision-maker hard to make decisions.

From the case study by applying the proposed model to the Yangtze River, it can be seen the selected option is unanimous with the real case, which means the proposed model is useful for emergency response to collision accidents. However, it should be mentioned that when applying this method to other waterways (e.g., the high sea), this decision-making may be different, for example, compared with the Yangtze River, there will not be so many shallow waters for beaching, and the crews have to prevent the ship from capsizing before the helicopter arrived.

Acknowledgements

The research presented in this paper was sponsored by a grant from National Science Foundation of China (Grant No. 51809206), National Key Technologies Research & Development Program (2017YFE0118000), the Fundamental Research Funds for the Central Universities (WUT:2019IVB062, WUT:2019IVB085) and the Hong Kong Scholar Program (No.2017XJ064).

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