A flexible decision-support solution for intervention measures for grounded ships in the Yangtze River

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Abstract: Groundings are frequently occurring accidents that pose a serious risk in inland waterways. This paper proposes a flexible decision-support solution for grounded ships in the Yangtze River. The basis of the proposed method is to develop an influence diagram based on a three-layer decision-making framework, to consider the effectiveness of the invention measures by adding two nodes and establishing the associated conditional probability tables, and to merge them as a flexible decision-support solution. The merits of the proposed method include the intuitive representation of how the influencing factors affect the alternatives using a graphical structure, the flexibility to implement and to consider the intervention measures for grounded ships, and the ability to deal with uncertainty in both numerical data and qualitative information. Consequently, the method presented in this paper provides a practical and flexible decision-support solution for grounded ships.

Key words: grounding accidents; flexible decision support; Bayesian network; intervention measures

1 Introduction

Maritime accidents have received considerable attention in recent decades owing to the high levels of property damage, casualties, and environmental pollution caused by such incidents. Of the various types of incident, collision accidents have attracted the most research attention. For example, Qu et al. (2011) analyzed collision risk by using Automatic Identification System data in Singapore Strait. Hänninen and Kujala (2012) discovered the influencing variables of collision accidents using a Bayesian network. Mou et al. (2010) proposed a dynamic method for collision risk analysis in Rotterdam Port. Further studies can also be found in the literature (Antão et al., 2008; Goerlandt and Kujala, 2014; Karahalios, 2014; Perera et al., 2012; Wang et al., 2013).

Another type of maritime accident that has attracted much interest is oil spill accidents. Vanem et al. (2008) presented cost-effectiveness criteria for oil spill preventive measures. Gouveia and Guedes Soares (2010) analyzed oil spill incidents in Portuguese Waters, Sebastião and Guedes Soares (2007) predicted oil spill trajectories in open sea, and Lee and Jung (2015) analyzed the pollution risk of oil spill accidents. Moreover, fire accidents (Soner et al., 2015) and flooding accidents (Jasionowski, 2011; Ölçer and Majumder, 2006; Santos and Guedes Soares, 2005; Santos and Guedes Soares, 2009; Varela et al., 2014) are also very important with respect to maritime transportation.

Secondary accidents may be caused by collision and grounding accidents (van de Wiel and van Dorp, 2009), and data show that grounding accidents rank second or third among all marine accident types (Yip, 2008; Zhang et al., 2013). Pedersen (2010) proposed ship collision and grounding analysis procedures. Kitamura (2002) used finite element analysis for the simulation of collision and grounding accidents. Mazaheri et al. (2014) presented a thorough review of grounding accidents from the perspective of risk management. (Uğurlu et al., 2015) discovered that human error is a key factor contributing to the occurrence of grounding accidents, and human fatigue is also significant for such incidents (Akhtar and Utne, 2014). Graziano et al. (2015) focused on the codification of grounding accidents.

Although many researchers have investigated risk mitigation for grounding accidents, work on decision-support frameworks and systems for such accidents, which require an early-stage response (Wu et al., 2016), is lacking from the literature. This is despite the large volume of work conducted on decision support for other types of maritime accidents. Wu et al. (2016) proposed a three-level hierarchical decision framework for handling out-of-control ships on the Yangtze River. Abi-Zeid and Frost (2005) proposed a decision-support system for search and rescue. Calabrese et al. (2012) presented a knowledge-based decision-support system for shipboard damage control, and Varela and Guedes Soares (2007) used virtual reality technology for ship damage control. Decision-support systems for flooding accidents have also received much attention (Jasionowski, 2011; Ölçer and Majumder, 2006; Varela et al., 2014), both in port areas (Mabrouki et al., 2014) and with respect to safety management (Akyuz and Celik, 2014).

However, some problems are apparent in existing models, especially in the hierarchical framework when applied to grounded ships. These problems include the following: (a) Such a framework cannot intuitively represent how the influencing factors affect the alternatives, (b) the framework has no flexibility to consider and ignore the influencing factors, and (c) the framework is unable to consider a variety of uncertainties. A detailed explanation of the drawbacks is presented in Section 2.

To address these aforementioned inadequacies of decision support for grounding accidents, this paper develops a flexible decision-support model based on influence diagrams. The remainder of the paper is organized as follows. Section 2 presents the Bayesian network method for decision-making and also analyzes the strengths of the proposed decision-making framework. Section 3 applies the proposed method for grounded ships and describes the influencing factors and alternatives in detail. Section 4 uses an illustrative example to verify the proposed method, and Section 5 presents the conclusions.

2 Bayesian network method for decision-making

2.1 Basic definitions of a Bayesian network

A Bayesian network is a directed acyclic graph, and it provides a tool for expressing both qualitative and quantitative relationships among multiple variables. A simple Bayesian network is shown in Fig. 1, and the graphical structure indicates that the natural environment is influenced by the time of day and wind speed. In this Bayesian network, the natural environment is denoted as the parent node, whereas the time of day and wind speed are denoted as child nodes. The network is also able to represent the quantitative relationships among the nodes. Taking Fig. 1 as an example, the probability table of wind means that grounding accidents occur during the day with a probability of 0.7 and during the night with a probability of 0.3. Day and night are denoted as states of the node of time of day. Similarly, the probability of wind speed can also be introduced in the same way; in the Bayesian network, this probability distribution is denoted as prior probability. The probability distribution of natural environment is denoted as the conditional probability table (CPT). Taking the first column of this CPT as an example, when the state of time of day is day, and the state of wind speed is less than 6, the natural environment is good with a probability of 0.8 and is bad with a probability of 0.2.

Moreover, defining a set of variables $X = (x_1, x_2, \cdots, x_n)$, the joint probability distribution can be expressed as follows. In the simple example of a Bayesian network shown in Fig. 1, the joint probability distribution can be computed with Equation 1 (using, for example, GeNIe software). More detailed information about Bayesian networks is contained in Eleye-Datubo et al. (2006).

$$\begin{aligned} P(x_1, \cdots x_n) &= P(x_1 \mid parent(x_1)) \\ &\quad \times P(x_2 \mid parent(x_2)) \cdots P(x_n \mid parent(x_n)) \\ &= \prod_{i=1}^{n} P(x_i \mid parent(x_i)) \end{aligned} \tag{1}$$

Insert Fig. 1 here

Recently, Bayesian networks have become widely used in applications in maritime transportation. This is because of four distinguishing characters of this technique. First, this technique provides an intuitive representation of the relationships among multiple variables (Eleye-Datubo et al., 2006; Zhang et al., 2013). Second, it also provides a probabilistic approach to quantifying the relationships among multiple variables (Fu et al., 2016; Montewka et al., 2013). Third, it can update the information using both historical data and expert judgments (Zeng et al., 2014; Zhang et al., 2013). Last, this technique can deal with uncertain information characterized by fuzziness and vagueness (Yang et al., 2008). In practice, Bayesian networks have been widely used for the analysis of human and organizational factors (Martins and Maturana, 2013; Mkrtchyan et al., 2015; Trucco et al., 2008), the risk analysis of maritime accidents (Akhtar and Utne, 2014; Goerlandt and Montewka, 2015; Hänninen and Kujala, 2012; Montewka et al., 2014; Zhang et al., 2016b), the reliability of search and rescue (Norrington et al., 2008), maritime safety management (Zhang et al., 2014b), the risk analysis of damaged ships (Kelangath et al., 2012), and intelligent ocean navigation and safety navigation (Perera et al., 2012; Pristrom et al., 2016).

2.2 Generic three-layer decision-making models

A generic decision-making model always consists of three layers (Qiu et al., 2014). Taking the selection of alternatives for handling uncontrolled ships, for example (Wu et al., 2016), the first layer contains multiple influencing factors, which requires the decision-maker to obtain prior information; the second layer contains the attributes; and the third layer contains the feasible alternatives. If all the influencing factors are treated as attributes, which means establishing a two-layer decision-making model, there will be too many attributes, thus confusing the decision-maker in the decision-making process (Wu et al., 2016).

Another problem should be addressed in the hierarchy decision model, which is the logical relationship between the variables and attributes. An intuitive structure should be established to describe how the influencing variables affect the associated attributes. The Bayesian network can deal with this problem well, owing to the graphical structure of such a network (Eleye-Datubo et al., 2006; Zhang et al., 2013).

The three-layer decision-making model based on a Bayesian network is shown in Fig. 2. Similar to the hierarchy decision model, the first layer contains multiple influencing variables, the second layer contains multiple attributes, and the third level contains multiple alternatives. By introducing the CPTs between the nodes, a three-layer decision-making model can be established. Three issues should be noted in this decision-making model. First, unlike the hierarchy decision model, where all the attributes are at the same level, one attribute (attribute 2) can be the parent node of another attribute (attribute 1). Second, as the utility value is introduced in this model, the decision-making model in this paper changes from a Bayesian network to influence diagrams. Third, the different layers are represented in different colours, and the decision-maker has to obtain only the prior information of the first layer, following which the utility values of each alternative can be automatically obtained, based on which the best alternative can be selected.

Insert Fig. 2 here

2.3 Improved decision-making model considering intervention measures

Traditionally, the generic three-layer decision-making model is reasonable and useful. However, some alternatives can be achieved only by using intervention measures for maritime accidents. For example, when using the self-refloating alternative, the captain must shift the cargo to make sure that the water depth is greater than the ship draft. In this example, shifting the cargo is one type of intervention measure, and the expected effectiveness of this intervention measure should be considered. Therefore, an improved model is proposed by adding another two nodes in the generic three-layer decision-making model, as shown in Fig. 3. In this proposed model, an adjusted node, denoted in yellow, is added as the parent node of the attribute node, and an intervention node is added as the child node of the adjusted node. In this way, the qualitative part of the relationships between intervention measures and attributes can be established (Fig. 3).

Insert Fig. 3 here

However, the most significant and difficult part of the proposed model is to define the quantitative relationships between intervention measures and attributes. There are three steps for achieving this. The first step is to define the linguistic variables of the intervention measure. As the effectiveness of intervention measure is always judged by the decision-maker before taking action, four linguistic variables are defined as the states of the node of intervention measure, which are “ineffective”, “effective”, “very effective”, and “definitely effective”.

The second step is to quantitatively define the effectiveness of the different states. The corresponding probabilities and descriptions of the states are defined in Table 1. It should be noted that all the probabilities are positive since all the intervention measures are assumed to be used to improve the performance of the evaluation variables; the intervention measures would not otherwise be used if the effectiveness of the intervention measures were negative. Another issue that should be noted is that the greatest probability used in this paper is 0.9 (rather than 1.0) and only discrete probabilities are used. This is because of three reasons. First, 0–9 scales (rather than 0–10 scales) have always been used in the risk analysis domains adopted in previous studies (Liu et al., 2013; Yang et al., 2008). Second, using a probability of 0.9 is sufficient to express that an improvement in the level of performance corresponding to “definitely effective” has been achieved. Third, a probability between 0.3 and 0.6 (also between 0 and 0.3 and between 0.6 and 0.9) can also be expressed using this method, as explained in the paragraphs below. The third step is to establish the relationship between the adjusted node and the node of intervention measures by introducing the CPT. The CPT for the example in Fig. 3 is given in Table 2.

Insert Table 1 here

Insert Table 2 here

The main principles of defining the CPT are as follows. First, the intervention measures that cannot improve the evaluation variables should be taken into consideration. This is achieved first by defining the state of intervention measure as "ineffective" and then establishing the relationships between the node of intervention measure and adjusted using the CPT. From the last column of Table 2, which is the conditional probability of "ineffective" given the "good" or "bad" states of evaluation variables, it can be seen that the states of these variables are totally transformed into the states of the adjusted node as the ineffective measures have been achieved.

Second, the improved level of performance should be quantified. When the intervention measures are effective, the "good" state of the evaluation variables is also transformed to the "good" state of the adjusted node, but the "bad" state will be changed (Table 2). Specifically, as the "effective" state of intervention has been defined to improve by 0.3 in Table 1, the 30% of the "bad" state is transformed to the "good" of the adjusted node, while the remaining 70% is transformed into the "bad" state of the adjusted node. In practice, this process can be easily carried out using the software GeNIe by setting the evidence on "effective" (Fig. 4). Fig. 4 shows that the state value of the adjusted node has been changed. Similarly, the "very effective" and "definitely effective" states of intervention can also be implemented.

Insert Fig. 4 here

Third, the probabilities between these discrete numbers (e.g., 0.51) should also be considered in this method. This can be achieved by defining the prior information as a distribution rather than setting evidence on one specific state of this node. In Fig. 3, the probability is 0.51 ($0.1 \times 0.9 + 0.6 \times 0.6 + 0.2 \times 0.3 + 0.1 \times 0$) by defining the prior information as a distribution: definitely effective, 0.1; very effective, 0.6; effective, 0.2; effective, 0.1.

2.4 Strengths of the proposed decision-making model

The proposed decision-making model is established by introducing the node of intervention measures and the adjusted node into the three-layer decision-making framework. In this paper, all the different types of nodes, including the influencing variables, evaluation variables, intervention measures, adjusted variables, and alternatives, are denoted in different colours. In practice, the decision-maker has only to obtain the prior information of the influencing factors and intervention measures; then, the expected utility values of each alternative can be obtained automatically by using the Bayesian inference algorithm.

In the context of the drawbacks of existing decision-making models, the proposed decision-making model has the following strengths. First, the decision-making model based on influence diagrams can intuitively represent the relationships among all the nodes using its graphical structure. Second, the proposed method can deal with both historical data and the domain of expert judgments. Traditionally, the data on the influencing factors are always collected from historical data so that it can take actions in limited time (Wu et al., 2016). However, the effectiveness of intervention measures should be judged according to the decision-maker's experience. Third, the proposed method needs to add only the nodes of intervention measures and adjusted nodes in the traditional three-layer decision-making model, which makes the method intuitive and easy to implement. Last, the proposed method considers the expert judgments on the intervention measures from a probabilistic perspective rather than using discrete numbers. As presented in Section 2.3, by defining the prior information of intervention measures as a probability distribution, any probability greater than 0 and less than 0.9 can be achieved in the proposed method.

3 Use of the proposed decision-support solution for grounded ships

3.1 Identifying the alternatives for grounded ships on the Yangtze River

According to statistical data for the Yangtze River, 215 grounding accidents occurred between 2009 and 2012. These historical data show that none of the accidents caused casualties or loss of the ship, and therefore the response actions to these accidents can be assumed to have been effective and reasonable. However, only

130 of these cases have detailed information about the process of accident development, including the cause(s) of the accidents, the development of the accidents, response actions to the accidents, and the results of the accidents. Statistical analysis shows that there are four alternatives for grounding accidents in the Yangtze River, namely, self-refloating (A1), waiting for high water (A2), run aground at full speed (A3), and tug assistance (A4). Further analysis reveals that alternative A2 is the most widely used, accounting for 38% of the 215 cases, with A1 accounting for 35%, A4 for 22%, and A3 for 5%. The detailed descriptions of these alternatives are as follows.

Self-refloating (A1): The grounded ship manages to refloat itself. Normally, ships run aground in a specific position rather than the whole. If the grounding position allows refloating by using intervention measures, the ship will have a high probability of self-refloating. There are also many intervention measures that can be carried out by the ship crew. For example, shifting the cargo to adjust the heeling and trim, using and using the astern speed if the grounding position is ship stem. However, it should be noted that these intervention measures can be used only in specific conditions and are influenced by many factors. A detailed description of all the interventions is presented in Section 3.3.

Waiting for high water (A2): The water level in the Yangtze River is constantly fluctuating from high water to low water and back to high water, and ships always run aground at the time of slack water or even low water. The grounded ship can wait for the high water until there is enough under-keel clearance (UKC) to float off.

Run aground at full speed (A3): The ship has no choice but to run aground at full speed to avoid a foundering accident because of the serious inclination of the ship or the rapid flooding of the grounded ship.

Tug assistance (A4): The grounded ship refloats with the help of external emergency resources, that is, a tug.

3.2 Determining the nodes in the three-layer decision-making framework

The nodes, including influencing factors and evaluation variables, can be obtained from both expert judgments and previous studies. As there are too many factors in the historical data, in this study experts were invited to identify the influencing factors. The groups and individuals invited to make expert judgments were: Jiangsu Maritime Safety Administration, the institution in charge of safety in the downstream part of the Yangtze River (Sun et al., 2013); Nanjing port tug and lighter company (NJP), a company who have been frequently requested to help grounded ships to refloat; the shipping company, SINOTRANS & CSC HOLDINGS CO., LTD; and a number of university professors who had previously worked as seafarers.

Moreover, influencing factors were also identified from previous studies. Twelve such factors were identified. Similar to collision accidents, the speed of grounding, river sediment conditions, the time of day, the arrival time of the ship, and the ship position of grounding (Montewka et al., 2014) are five important factors. Wind speed and ship dead weight tonnage (DWT) are two further significant influencing factors (Balmat et al., 2011; Wu et al., 2015). The river level during grounding and the river level during refloating (Li et al., 2014; Zhang et al., 2013) are related to UKC, especially on the Yangtze River. Restricted area (Wu et al., 2016) is an obstacle to taking response actions. The influencing factors of the heeling and trim of grounded ships are derived from the expert judgments, and these are important to refloat the grounded ship.

To assist the decision-maker, and in a similar way to the hierarchical model, the influencing factors are integrated in terms of their categories to reduce the number of attributes. Eight evaluation variables are defined in this paper, namely, natural environment, mechanical damage, the feasibility of waiting for high water, use of the anchor, hull damage, vessel condition, and UKC. The relationships among all nodes in the three-layer decision-making framework (introduced in Section 2.2) are shown in Fig. 5. Some of these nodes were obtained from previous studies, including natural environment (Wu et al., 2016), vessel condition (Wu et al., 2016), hull damage (Prestileo et al., 2013; Santos and Guedes Soares, 2005), mechanical damage (Montewka et al., 2014), and the speed of ship flooding (Montewka et al., 2014), UKC (Zhang et al., 2013), whereas others were derived from the domain of expert judgments. Moreover, the relationships between alternatives and other nodes were also obtained from the domain of expert experience.

Insert Fig. 5 here

3.3 Applying the proposed method to obtain the graphical structure

Other important nodes are the intervention measures and the adjusted nodes. There are four intervention measures for grounded ships: the shifting of cargo (B1), the unloading of ballast water and cargo (B2), the stoppage of leaking (B3), and the discharge of flooding water (B4). Detailed descriptions of these four intervention measures are as follows.

Shift the cargo (B1). Shifting the cargo can change the heeling and trim of the grounded ships. According to the domain of expert experience, when the ship is half load, reducing one degree of heeling will cause the ship draft to reduce by 1.7%, whereas changing six degrees of heeling will cause the ship draft to reduce by 10%. Moreover, the trim can also be adjusted by shifting cargo to make the ship refloat. For example, when the grounding position is stern and the water depth is sufficient in the other parts of the ship (amidships and stern), the captain can shift the cargo from stem to stern to make the stem refloat.

Unload ballast water and cargo (B2). The ship runs aground because there is insufficient water depth with respect to its draft. This intervention measure manages to reduce the ship draft by unloading the ballast water and cargo so that the UKC will be increased to make the ship refloat.

Leak stoppage (B3): if the ship hull is seriously damaged, the ship will flood quickly. This intervention measure manages to reduce/stop the water inflow.

Discharge of flooding water (B4): This intervention measure manages to discharge the existing water inflow.

Considering the effectiveness of these four intervention measures, the associated nodes should also be changed. By introducing the method described in Section 2.3, six adjusted nodes were added: adjusted UKC, the adjusted heeling of grounded ships, the adjusted trim of grounded ships, adjusted vessel condition, the adjusted speed of ship flooding, and adjusted flooding water. The adjustments made by considering the intervention measures are shown in Fig. 6, where Fig. 6 (a) shows the adjustments considering the intervention measures of unloading ballast water and cargo and shifting cargo, and Fig. 6 (b) shows the adjustments considering the intervention measures of leak stoppage and discharge of flooding water.

Insert Fig. 6 here

By merging Figs 5 and 6, the proposed decision-making model for grounded ships considering the intervention measures can be formulated as shown in Fig. 7. It should be mentioned that a sub-model in the GeNIe software is used to simplify the graphical structure. In Fig. 7, there are three sub-models, which are vessel condition, adjusted vessel condition, and adjusted flooding water. As described in Section 2.4, the decision-maker has to obtain the prior information of the influencing factors and intervention measures. Therefore, the sub-model contains only the evaluation variables or adjusted variables, while all the influencing variables can be seen from this graphical structure. The first sub-model is vessel condition, which includes the nodes of UKC, hull damage, and vessel condition. The second sub-model is adjusted vessel condition, which includes the nodes of the adjusted heeling of grounded ships, the adjusted trim of grounded ships, adjusted UKC, and adjusted vessel condition. The third sub-model includes the speed of ship flooding, the adjusted speed of ship flooding, and adjusted flooding water. The relationships among these nodes can be seen in Figs 5 and 6.

Insert Fig. 7 here

3.4 Defining the states of the variables for grounded ships

The most important way to define the states of the variables is in terms of the damage to the grounded ships or the influence of the intervention measures. However, if there are too many states, there will be too many conditional probabilities to be established (Yang et al., 2008). For example, if the parent node has three child nodes, and each node has four states, there will be 64 (4 × 4 × 4) conditional probabilities. Therefore, if the states of each node are always less than 3, then it will not significantly influence the accuracy of the result. The states of the influencing factors are given in Table 3.

Insert Table 3 here

The states of the evaluation variables are slightly different from the states of the influencing factors. As the evaluation variables are established to facilitate the decision-making process for the decision-maker, the states of these variables should make it easy for the decision-maker to make judgments. The states and their explanations are given in Table 4.

Insert Table 4 here

The states of the intervention measures in this paper, including shifting cargo, unloading ballast water and cargo, leak stoppage, and discharge of flooding water, are the same as those of the intervention measures described in Section 2.3. Specifically, they are “ineffective”, “effective”, “very effective”, and “definitely effective”.

3.5 Developing the extended IF–THEN rules to establish the CPTs

Developing if–then rules is the most important but also most difficult step in the development of the decision-making model for grounded ships. The most widely used method for developing such rules is to use the available statistical data (Kelangath et al., 2012; Zeng et al., 2014; Zhang et al., 2014a). However, this method is hard to implement in this paper because of two reasons. First, there are only 130 cases of grounded ships with detailed information, which is not enough to obtain convincing results. Second, but more importantly, the evaluation variables, which are developed to help the decision-maker, have no statistical data.

Another common method is to use the domain of expert judgments in the extended IF–THEN rules schemes (Yang et al., 2008). Taking the natural environment in Fig. 1 as an example, the traditional IF–THEN rules, which are always used in fuzzy logic (Wu et al., 2016), can be established as follows.

If the time of day is *day* and the wind speed is *less than 6* (Beaufort scale), then the natural environment is *good*.

However, this method cannot accurately describe the output variables (natural environment). To improve the description of these variables, the extended IF–THEN rule can be established as follows (Yang et al., 2008).

If the time of day is *day* and the wind speed is *less than 6*, then the natural environment is *good* with a belief degree of 0.8, and the natural environment is *bad* with a belief degree of 0.2.

It can be seen that this extended rule is the first column of the CPT for natural environment in Fig. 1. To obtain the complete CPTs in the proposed decision-making model, four experts from the above-mentioned universities or companies in Section 3.2 were invited to give judgments by using the extended rules. Their average value was used for each extended rule. In this paper, only the CPT for the evaluation variable of the feasibility of waiting for high water is given as an example, but the experts' explanations of judgments of all evaluation variables are described in detail in the paper.

The CPT for the feasibility of waiting for high water is given in Table 5. The experts argue that only when the river level of refloating is higher than the river level of grounding is waiting for high water a feasible intervention. Moreover, the higher the river level, the higher the feasibility.

Insert Table 5 here

The experts' explanations of other CPTs are as follows. When the river sediment is soft, the grounding position is stern, and the ship has run aground at full speed, the rudder and paddle will have a high likelihood of being damaged, which is denoted as mechanical damage. When the time of day is night, the wind speed is greater than 6, and the restricted area is close to the location of the grounded ship, the natural environment is regarded as being bad. When the ship's DWT is greater than 10,000 DWT, it will be very hard to use the anchor for assistance. When the speed of grounding is high, and the river level of grounding is high water, the UKC is assumed to be better than in other scenarios. In fact, from the expert evaluation provided, only when the UKC is greater than 30 cm can the ship be refloated, as when the UKC is smaller than this value, the grounded ship is stuck deep into the river bed. Hull damage is assumed to be serious when the river sediment is hard, the speed of grounding is high, and the river level of grounding is high water. But if the river sediment is soft, the hull damage will be only slight. The vessel condition is good when the UKC is greater than 30 cm and the hull is slightly damaged. The speed of flooding is quick when the hull is significantly damaged.

3.6 Introducing utility value for final decision-making

We introduce utility value for final decision-making in this paper. In such a way, the IF–THEN rules are used twice to obtain the relationships between alternatives and their parent nodes. Taking the alternative of self-refloating as an example, the CPT is established as given in Table 6. The first line of that table, indicated as self-refloating (damaged), is the utility value under the condition of mechanically damaged, whereas the second line is the utility value under the condition of mechanically undamaged. When the mechanical condition is undamaged, the natural environment is good, and the adjusted vessel condition is also good, there will be a high likelihood of success for implementing the self-refloating alternative.

Insert Table 6 here

Similarly, waiting for high water is influenced by the use of the anchor, mechanical damage, natural environment, and the feasibility of waiting for high water. Running aground with full speed is influenced only by the adjusted flooding water because this alternative is always the last choice and can be used only when a grounded ship is flooding quickly. Tug assistance is always carried out when the arrival time is short, the mechanical damage is undamaged, the natural environment is good, and the adjusted flood water is few.

Finally, the decisions are made using the Bayesian inference algorithm, that is, the joint probability distribution introduced in Section 2.1. The computations and analysis can be performed by using GeNIe software.

4 An illustrative example

4.1 Scenario description

To verify the proposed model, we used as an example a ship grounding that occurred in 2010 in the Yangtze River. The ship grounded around 1,700 m downstream of the second Nanjing Yangtze River bridge. The accident occurred at 0030 local time (GMT+8), and the ship was fully loaded.

The detailed information is as follows: ship length, 79.4 m; ship DWT, 3,900 t; wind Beaufort scale, from 4 to 5. River sediment, soft; ship position of grounding, stem; speed of grounding, slow speed; river level of grounding, slack water; arrival time of tug, less than 15 minutes because the accident location was close to the second Yangtze River bridge; restricted area (bridge in this case), 1,700m; time of day, night; heeling of the flooding ship, no.

The interventions judged by the experts are as follows. Shifting cargo, effective; unloading ballast water and cargo, very effective; leak stoppage, effective; discharge of flooding water, effective.

4.2 Input of prior information regarding the influencing factors and intervention measures

By introducing the prior information of this accident, the evaluation variables and expected values of each alternative can be obtained using the Bayesian inference algorithm. In the GeNIe software, it is easy to implement this process by using “set evidence” on each node. For example, when inputting the prior information of river sediment as “soft”, the decision-maker has only to select “set evidence” on the “soft” state after right-clicking on this node. All the other nodes can be treated in the same way. The graphical structure of the result is shown in Fig. 8.

Insert Fig. 8 here

The results for all the evaluation variables for the studied case are given in Table 7. It should be noted that some of the evaluation variables are contained in the three sub-models, which are not shown in Fig. 8.

Insert Table 7 here

For this grounding incident, the mechanical damage is undamaged with a probability owing to the soft river sediment and grounding in the amidships part of the ship (Table 7). Waiting for high water is unfeasible because the river level of the grounding and the river level of refloating are the same (both river levels are slack water). The natural environment is not good at night. However, the use of the anchor to assist refloating is feasible owing to the small size of the grounded ship. Hull damage is slight or moderate because the speed of grounding is slow, the river sediment is soft, and the river level of grounding is slack water. The adjusted nodes, including the adjusted heeling of the grounded ship, the adjusted trim of the grounded ship, the adjusted UKC, the adjusted vessel condition, the adjusted speed of ship flooding, and adjusted flooding water, are compared in Section 4.4.

4.3 Identifying the best intervention alternative for the grounded ship

With respect to identifying the best intervention for the grounded ship studied in this scenario, Fig. 7 displays the utility values of each alternative and the results are reported in Table 8.

Insert Table 8 here

The best intervention alternative for the grounded ship in the studied case is self-refloating, which is indicated as A1. This is the same with the alternative used in reality. The A1 alternative is best because the rudder and paddle are not damaged and available to control the ship; moreover, the adjusted vessel condition is good, and the natural environment is not too unfavourable. A4 ranks second, and this alternative can also be used for the grounded ship in this case. However, because the ship can unload its own cargo to refloat itself, whereas the A4 alternative needs external resources (i.e., tug assistance), A1 is assumed to be better than A4. Waiting for high water (A2) is the worst alternative because the river level of refloating and the river level of grounding are the same; therefore, it is unfeasible to wait for high water in this case. Running aground at full speed (A3) is, generally speaking, the worst option. However, in this case study, because the flooding can be prevented by leak stoppage and discharge of flooding water, and the alternative of waiting for high water is very hard to implement, this alternative ranks third.

4.4 Comparison with the results ignoring the intervention measures

The decision-making process ignoring the intervention measures is carried out by setting the states of the four intervention measures to "ineffective". The results using GeNIe software are shown in Fig. 9. Some of the evaluation variables are different from the adjusted nodes by considering the intervention measures, and the state values of the unadjusted nodes are reported in Table 9. Specifically, the adjusted heeling of the grounded ship is unfeasible since there is no heeling to be adjusted, and even if the intervention measure (shifting cargo) is definitely effective, the result will be the same, and the adjusted heeling will not be changed. However, UKC is good because the speed of grounding is slow and the river level of grounding is slack water, while the adjusted UKC is improved since unloading cargo is very effective in this case. Consequently, the adjusted vessel condition is also improved. The speed of ship flooding is the same with hull damage. Similarly, the adjusted speed of ship flooding and the adjusted flooding water are also improved as the intervention measures (including leak stoppage and discharge of flooding water) are effective.

Insert Fig. 9 here

Insert Table 9 here

The final decision-making results for grounded ships are given in Table 10, from which it can be seen that the best alternative is A4 when ignoring the effectiveness of intervention measures. The difference is because of the following reasons. First, as the intervention measures can improve the vessel's condition, this will influence the possibility of successfully using the alternative of self-refloating. The self-refloating alternative will have a higher probability of success than not taking any intervention measures. However, tug assistance is the same as the result obtained ignoring the intervention measures. Second, in reality, as the ship can refloat itself by unloading cargo, the alternative of tug assistance is worse than the self-refloating option because the tug intervention requires external resources. However, when ignoring the intervention measures, which means that the decision-maker does not know whether unloading cargo is possible, the decision-maker has to choose a feasible solution for the grounded ship even though it needs the help of a tug.

Insert Table 10 here

4.5 Decision-making for grounded ships under uncertainty

One merit of the proposed decision-making model is that it can deal with a variety of uncertainties, including both qualitative information and numerical data. Specifically, the qualitative information is the fuzziness and vagueness in describing the influencing factors, and linguistic terms are always used to express this uncertain information (Wu et al., 2016). The numerical data comprise the probability distribution of the linguistic variables (Zhang et al., 2016a). For example, when describing wind speed, the linguistic terms "less than 3", "from 3 to 6", and "more than 6" are used to describe the qualitative information. However, sometimes the wind may change, and statements such as "less than 3" with a probability of 0.4, "from 3 to 6" with a probability of 0.4, and "more than 6" with a probability of 0.2 are used; this uncertainty is generated by the numerical data. In the proposed decision-making model, it is easy to deal with these two types of uncertainties.

To illustrate that the proposed decision-making model can deal with uncertainty, all the prior information, including influencing factors and intervention measures, were defined as a probability distribution similar to that of the wind speed example mentioned above. The result is shown in Fig. 10. It should be noted that any probability distribution of these nodes can be implemented in this graphical structure, which makes this model easily applicable to other research domains.

Insert Fig. 10 here

5 Concluding remarks

The main contribution of this paper is to propose a flexible decision-support solution for grounded ships considering the range of possible intervention measures. This decision-support solution is beneficial for grounded ship handling because it has the following strengths. (a) It provides a graphical structure to represent how the influencing factors affect the alternatives. (b) It is easy to implement because the decision-maker has only to obtain the information of the nodes of influencing factors and the intervention measures, following which the values of the evaluation variables and alternatives can be automatically generated. (c) It is sufficiently flexible to consider new influencing factors or to ignore some existing influencing factors if it is difficult to obtain the required information in the time available. (d) It has the flexibility to consider the intervention measures from a probabilistic perspective. (e) It is able to deal with uncertain information including both numerical data and qualitative information.

Although the method has the above strengths, some weaknesses also exist. For example, the decision-support solution is proposed based on data for the Yangtze River, which is characterized by a narrow channel, limited depth, dense traffic, and the disturbance of crossing ships. When applying this method to other waterways (e.g., the open sea), the alternatives and influencing factors may be different, and some adjustments should be made. Moreover, the proposed method can also be applied to other fields if the problem is sufficiently flexible to consider the effectiveness of intervention measures and to be able to provide an intuitive representation of the relationships among multiple nodes.

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Table 1 Probabilities and descriptions of the states of intervention measures

states	probability	description
definitely effective	0.9	The bad performance of the associated node can be improved by 0.9.
very effective	0.6	The bad performance of the associated node can be improved by 0.6.
effective	0.3	The bad performance of the associated node can be improved by 0.3.
ineffective	0	The bad performance of the associated node cannot be improved.

Table 2 CPT for intervention measures and adjusted node

intervention measures	definitely effective		very effective		effective		ineffective	
evaluation variables	good	bad	good	bad	good	bad	good	bad
good	1	0.9	1	0.6	1	0.3	1	0
bad	0	0.1	0	0.4	0	0.7	0	1

Table 3 States of the influencing factors and their explanations

nodes	states	explanations
ship position of grounding	stem/amidships/stern	As the rudder and paddle are in the stern; therefore, the closer to the stern of the grounding, the higher the likelihood of mechanical damage being caused.
river level of refloating	slack/high water	The ship is grounded owing to insufficient water depth at low water or even slack water.
speed of grounding	full/half/slow	The higher the speed of grounding, the more serious the damage to the grounded ship.
river level of grounding	low/slack/high water	The lower the river level of grounding, the more serious the damage to the ship.
river sediment	soft/hard	Hard river sediment has a higher likelihood of causing serious damage to the grounded ships than does soft sediment.
restricted area	less than 1 km / from 1 km to 3 km / more than 3 km	The response action to the grounded ship will be seriously influenced if a restricted area (such as a bridge) is less than 1 km away and will be little influenced if the restricted area is more than 3 km.
time of day	day/night	Response actions to grounded ships at night will be influenced by poor visibility.
wind speed (Beaufort scale)	less than 3 / from 3 to 6 / more than 6	The ship will be prohibited from navigating when the wind speed is more than 6 in the channel in the Yangtze River, but there is little influence on the ship when the wind is less than 3.
ship DWT	less/more than 10,000 DWT	A ship of less than 10,000 DWT can use the anchor to assist refloating, whereas one of more than 10,000 DWT cannot feasibly use the anchor for assistance.
arrival time of tug	less than 15/30/45 minutes	The arrival time of the tug is very important because of the limited time for attending to an emergency on the Yangtze River; the arrival time is defined according to the distance to the port.
trim of grounded ship	feasible/unfeasible for adjustment to make ship refloating	The trim is feasible or unfeasible of being adjusted to make the grounded ship refloat.

heeling of grounded ship	yes/no	There is heeling / no heeling to be adjusted to make the grounded ship refloat.

Table 4 States of the evaluation variables and their explanations

nodes	states	explanations
mechanical damage	damaged/undamaged	The rudder and paddle are damaged or undamaged.
feasibility of waiting for high water	feasible/unfeasible	It is feasible/unfeasible for the grounded ship to wait for high water to make the ship refloat.
natural environment	good/normal/bad	The natural environment is good/normal/bad for refloating.
use of anchor	feasible/unfeasible	It is feasible/unfeasible for the grounded ship to use the anchor for assistance.
UKC	below 30 cm / from 30 to 50 cm / above 50 cm	The UKC is below 30 cm / from 30 to 50 cm / above 50 cm.
hull damage	seriously/moderately/ slightly	The hull is seriously/moderately/slightly damaged.
vessel condition	good/normal/bad	The vessel condition is good/normal/bad.
speed of ship flooding	quickly/moderately/slowly	The ship flooding speed is quick/moderate/slow.

Table 5 CPT for the feasibility of waiting for high water

river level of refloating	high water			slack water		
river level of grounding	high water	slack water	low water	high water	slack water	low water
feasible	0.2	0.7	0.95	0	0.2	0.7
unfeasible	0.8	0.3	0.05	1	0.8	0.3

Table 6 CPT for the intervention alternative of self-refloating

mechanical damage	damaged/undamaged								
natural environment	good			normal			bad		
adjusted vessel condition	good	normal	bad	good	normal	bad	good	normal	bad
self-refloating (damaged)	0.55	0.45	0.35	0.4	0.3	0.2	0.3	0.3	0.1
self-refloating (undamaged)	0.9	0.8	0.5	0.8	0.7	0.4	0.4	0.3	0.2

Table 7 State values of the evaluation variables

node	State 1	State 2	State 3
mechanical damage	damaged 0.15	undamaged 0.85	-
feasibility of waiting for high water	feasible 0.20	unfeasible 0.80	-
natural environment	good 0.20	normal 0.40	bad 0.40
use of anchor	feasible 0.90	unfeasible 0.10	-
hull damage	severely 0.10	moderately 0.50	slightly 0.40
adjusted heeling of grounded ship	feasible 0.00	unfeasible 1.00	-
adjusted trim of grounded ship	feasible 0.90	unfeasible 0.10	-
adjusted UKC	<30 cm 0.01	30 to 50 cm 0.23	>50 cm 0.76
adjusted vessel condition	good 0.71	normal 0.20	bad 0.09
adjusted speed of ship flooding	quickly 0.14	moderately 0.30	slowly 0.56
adjusted flooding water	many 0.10	average 0.25	few 0.65

Table 8 Final decision-making for the alternatives

alternatives	abbreviation	utility	ranking
self-refloating	A1	0.572	1
waiting for high water	A2	0.247	4
run aground at full speed	A3	0.328	3
tug assistance	A4	0.561	2

Table 9 State values of the evaluation variables ignoring intervention measures

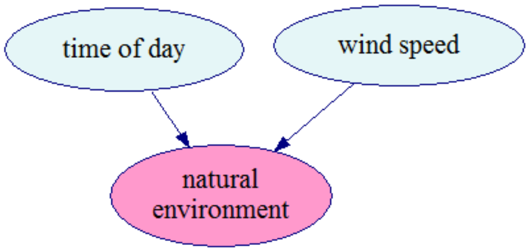
node	State 1	State 2	State 3
trim of grounded ship	feasible 0.90	unfeasible 0.10	-
UKC	<30 cm 0.25	30 to 50 cm 0.30	>50 cm 0.45
vessel condition	good 0.49	normal 0.28	bad 0.23
speed of ship flooding	quickly 0.10	moderately 0.50	slowly 0.40

Table 10 Decision-making ignoring the intervention measures

alternatives	abbreviation	utility	ranking
self-refloating	A1	0.556	2
waiting for high water	A2	0.240	4
run aground at full speed	A3	0.446	3
tug assistance	A4	0.561	1

time of day	probability
day	0.7
night	0.3

wind speed (Beaufort scale)	probability
Less than 6	0.6
more than 6	0.4



time of day	day		night	
wind speed	less than 6	more than 6	less than 6	more than 6
good	0.8	0.6	0.7	0.4
bad	0.2	0.4	0.3	0.6

Fig. 1 A simple Bayesian network

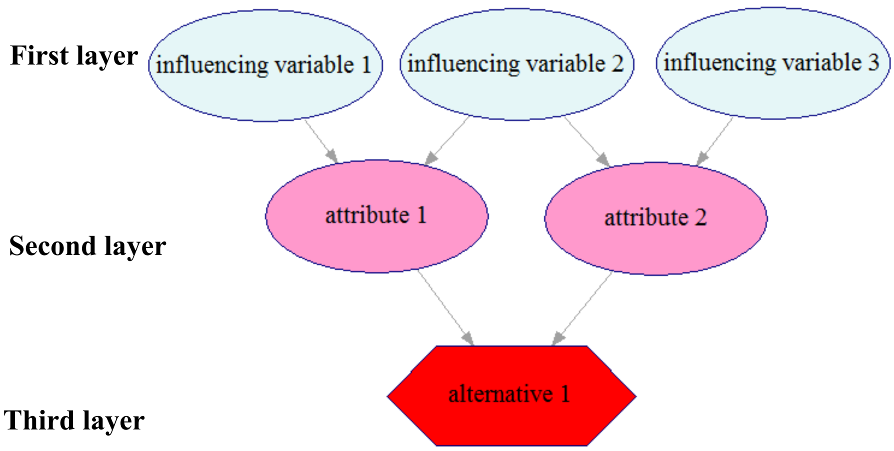


Fig. 2 Generic three-layer decision-making framework

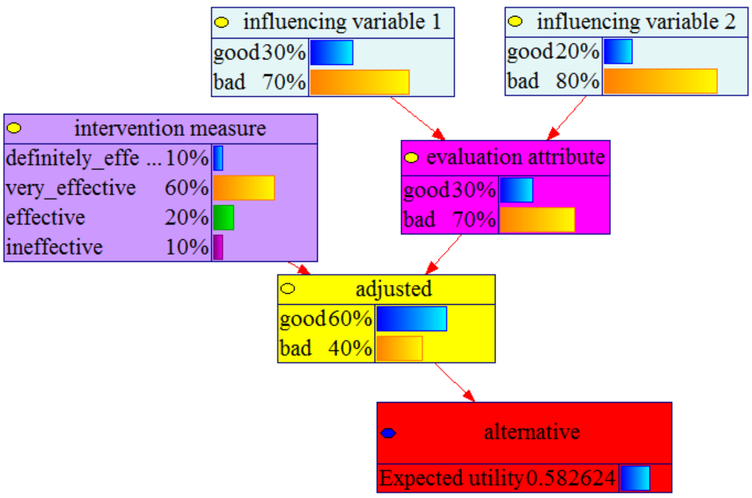


Fig. 3 Proposed model considering intervention measures

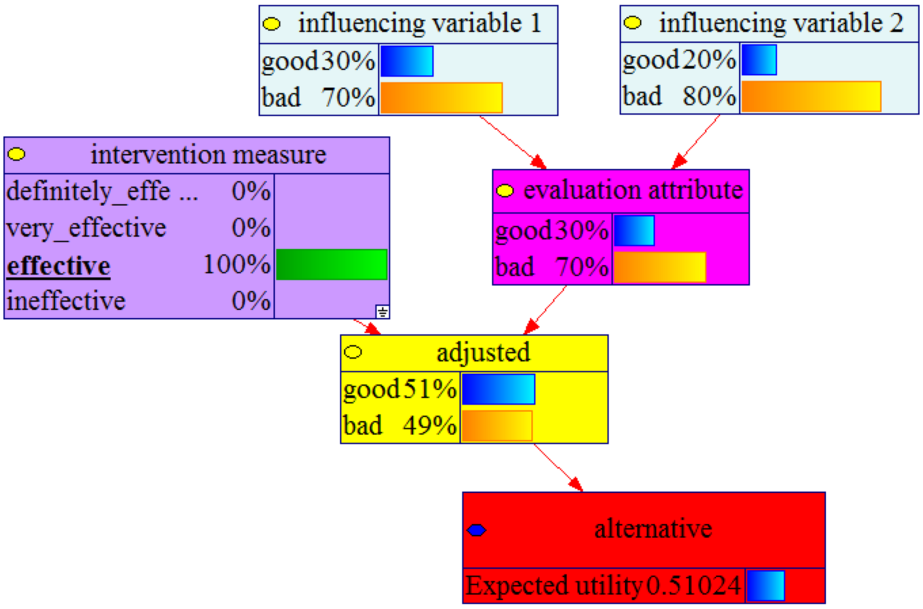


Fig. 4 Implementation of the intervention measures by setting evidence

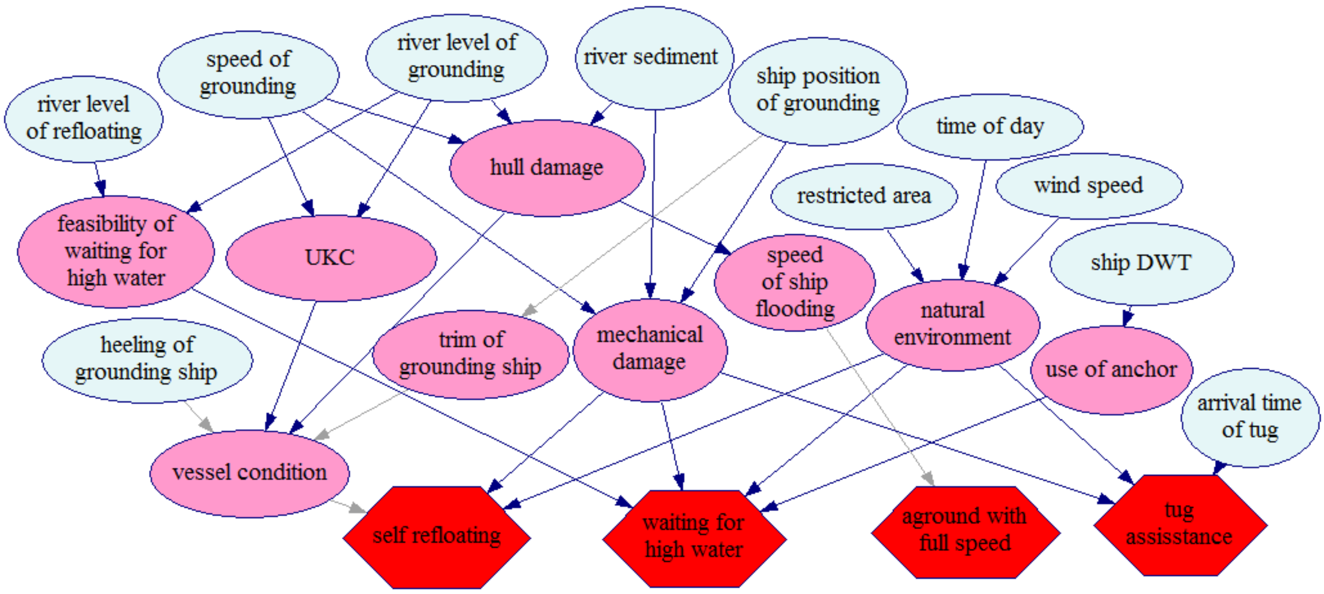


Fig. 5 Graphical relationships in the three-layer framework

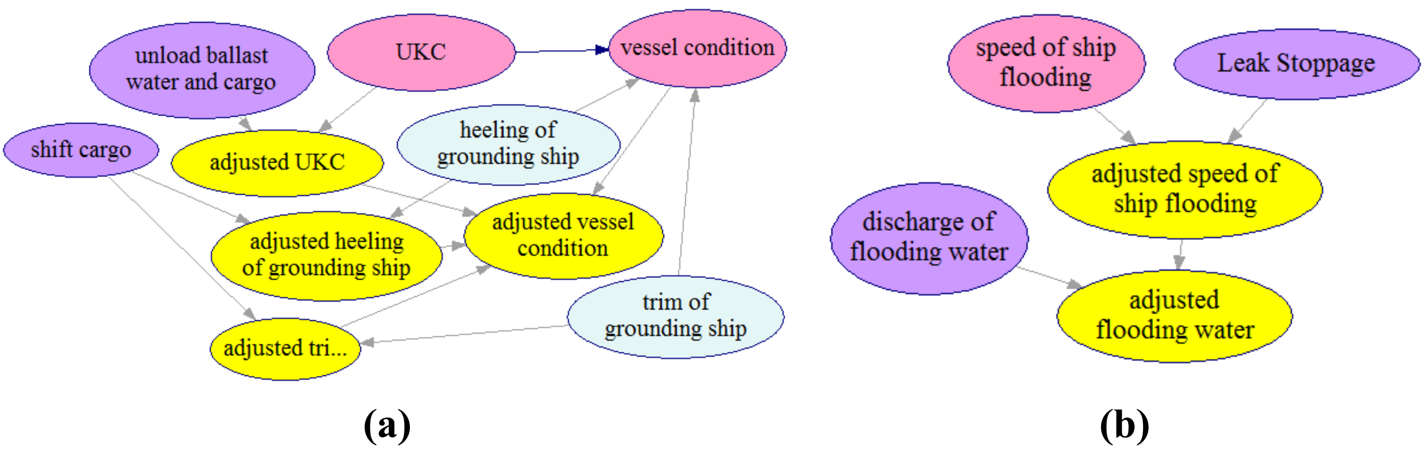


Fig. 6 Adjustments considering the intervention measures

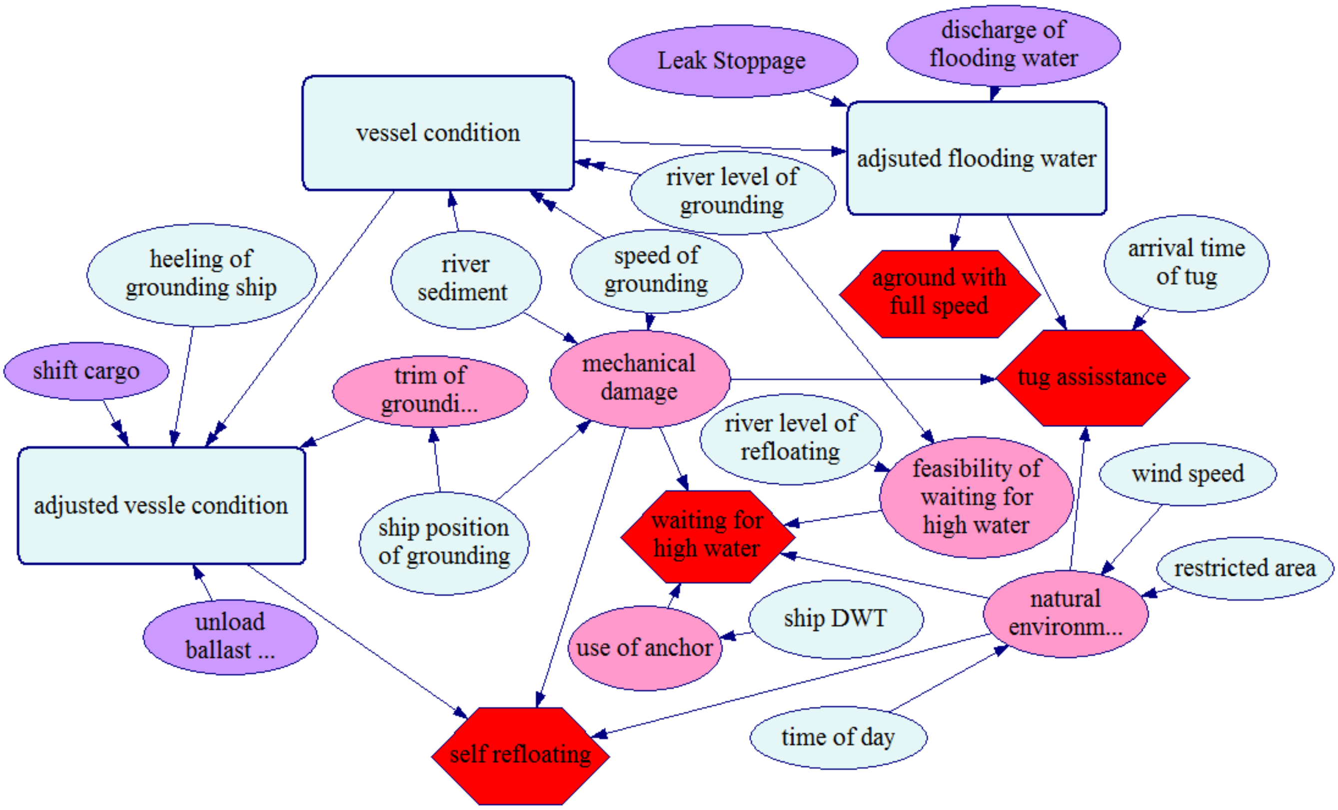


Fig. 7 Proposed decision-making model considering intervention measures

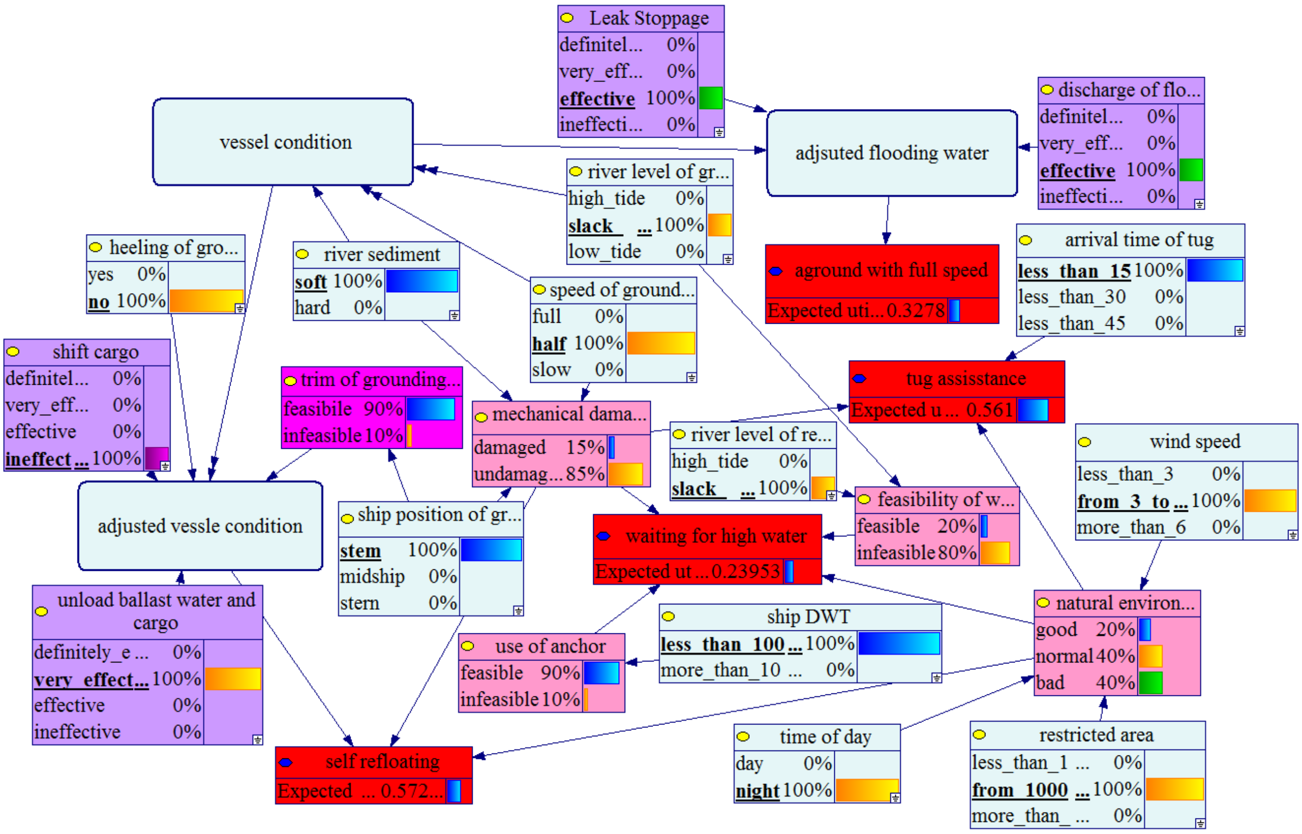


Fig. 8 Graphical structure of the result after inputting the prior information

Fig. 9 State values of the evaluation variables ignoring intervention measures

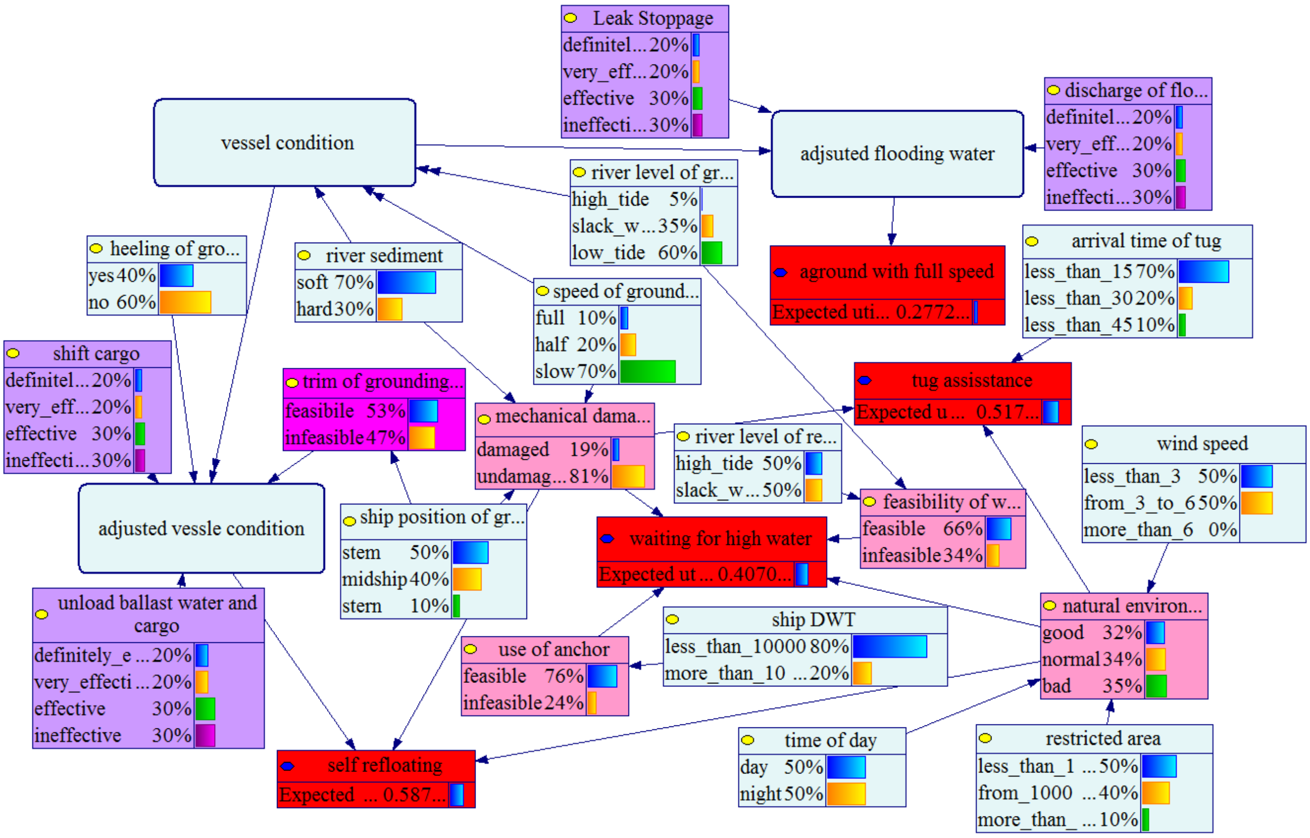


Fig. 10 Decision-making for grounded ships under uncertainty