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# A quantitative decision-making model for emergency response to oil spill from ships

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**Abstract:** Oil spills from ships pose a serious threat to the marine environment and causes great losses of energy sources. The emergency response to oil spill from ships is challenging owing to the time limitation and resource constraint, together with the lack of historical data. This paper manages to propose a quantitative decision-making model for emergency response to oil spill from ships to address the abovementioned problems. The kernel of this model is first to establish a hierarchical decision-making framework after identification and quantification of the influencing factors and alternatives from previous studies, and to integrate them by using evidential reasoning algorithm while the weights are obtained by using linguistic terms. This proposed model is applied to a real oil spill from ships, and the result demonstrates that the proposed model is reasonable to select the best response action to oil spill from ships.

**Key words:** maritime safety, decision-making, oil spill from ships, emergency response, quantitative model

## 1 Introduction

Oil spills from ships pose a serious threat to the marine environment and cause great losses of energy sources. From Yip et al. (2011), the oil spill accident is the second and third most frequently occurring accident expect for the collision and grounding accidents in maritime transportation, respectively. In China, more than 70 oil spill accidents occurred during 1990-2010 and these accidents caused more than 50 tons of spilled oil from ships (Xiong et al., 2015). Therefore, many researchers have focused on the risk control of such accident worldwide, including coastal area, open sea, inland waterway and arctic area. Vanem et al. (2008) presented cost-effectiveness criteria for oil spill preventive measures by considering all costs of a shipping accident, and their criteria are applied to oil tanker spill accidents. The causation distribution of oil spill incidents is analysed in Portuguese Waters (Gouveia and Guedes Soares 2010). Sebastião and Guedes Soares (2007) predicted oil spill trajectories using numerical simulation in open sea. Lee and Jung (2015) analyzed the pollution risk of oil spill accidents by using both the impact probability of the oil spill and determined the first impact time of the spilled oil. Lan et al. (2015) proposed a marine oil spill risk mapping model and applied it to the Dalian port to identify the risk level of different zones. Bi and Si (2012) proposed a dynamic risk assessment model for oil spill in the three gorges reservoir, where the water level fluctuates from 145m to 175m, and the oil spill and the consequence including the marine environment and social effects are taken into consideration. Garrett et al. (2017) proposed a mixed-integer linear program to improve oil spill response capabilities to support energy exploration in the Arctic.

Although some studies have been conducted, the majority of previous studies focus on the risk analysis of the oil spill accidents using the formal safety assessment (FSA) framework. However, the decision support system for response to oil spill accidents, which requires an earlier response to maritime accidents (Wu et al., 2016), is missing from the literature (Xiong et al., 2015). In order to develop a decision support system, one of its kernels - the decision-making model - should be developed first.

In previous studies, emergency decision-making is a widely used technique for safety control of maritime accidents. Wu et al. (2016) proposed a hybrid group decision-making model for not-under-control ships in the Yangtze River by using historical data. In that paper, a three-layer decision-making framework is established and the influencing factors are integrated by using the fuzzy logic method. An extended work was also presented by Wu et al. (2017b), where the decision-making model is first to use case-based reasoning to select the basic feasible options, and then to develop a merging Bayesian network for the cooperation among multiple involved organizations. Recently, Wu et al. (2017c) proposed a Bayesian network based decision-making model for the intervention measures of the grounded ships in the Yangtze River. Krohling and Campanharo (2011) proposed a fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method for selection of the best combat action to oil spill in the oil field of Jubarte. Calabrese et al. (2012) proposed knowledge-based decision support system for shipboard damage control and used a national navy as an example to illustrate that the proposed system is useful and practical. Jasionowski (2011) reviewed and analyzed three typical flooding accidents, and proposed a decision support system for flooding accidents.

It can be seen from the abovementioned works that the models for different types of maritime accidents vary as each type of accident own its distinguishing features. Therefore, in order to develop a decision-making model for emergency response to oil spill from ships, the characteristics of oil spill from ships should be discussed. Compared to other types of maritime accidents, the distinguishing features of oil spill accidents should be analyzed and modelled. The challenges for decision-making of oil spill from ships are summarized as follows.

The first challenge for emergency response to oil spill from ships is lack of historical data. Although more than 70 cases have been collected from the previous work in China (Xiong et al., 2015), these data only include the time of the accident occurred, the coordinates of the oil spill accidents, the ship type, how many tons of oil spilled, the pollution type, and the incident type. However, few of the data include the response actions and the available emergency resources for the oil spill accidents. Moreover, the number of oil spills is not large enough to establish data-driven analysis. Therefore, it is difficult to establish the decision-making framework based on the historical data. Unavailability of data is the first challenge to analyse the emergency response to oil spill from ships.

The second challenge for emergency response to oil spill from ships is time limitation. Similar with other types of maritime accidents (Wu et al., 2017b; Jasionowski, 2011), oil spills from ships are limited in time. From the historical data during 1990-2010 in China (Xiong et al., 2015), oil spill accidents are often a secondary accident and most of them are caused by another type of maritime accidents. To be specific, 58.2% of oil spill from ships are caused by collision accidents, 16.4% of them by collision and stranding, while there is only one accident caused by operation errors, which only accounts for 1.5%. If a maritime accident occurs in a fairway, quick response actions are required but otherwise passing ships would be significantly influenced (Wu et al., 2017b) and cause traffic congestion (Zhang et al., 2013). Moreover, compared to an oil spill from offshore drilling platforms, the oil spill volume from ships are relatively small. From the same historical data, the most spilled oil volume is 2,000 tons, and only 12 cases spilled oil more than 500 tons. Therefore, the maritime safety administration should have the capability to take response actions, because the spilled volume of oil in one marine accident is not too large to be handled.

The third challenge for emergency response to oil spill from ships is resource constraint, which is also common in other types of maritime accidents (Wu et al., 2017b; Shi et al., 2014). Although the spilled oil volume is small, which implies the required emergency resources is also small, the response to oil spill from ships is also constrainted by rescue resources. This is owing to the offshore feature of the maritime transportation. In China, the resources are required to arrive in 15, 30 and 45 minutes in terms of the distance from the resource site to the accidental scene. Moreover, as the different types of resources may be different in distance, the arrival time may also be different in practice. Moreover, as the response to the oil spill accidents are limited in both time and resources, this is also the reason why this paper only considers the initial response action rather than the combined response action because the initial action is the most important and can control an spill effectively.

This paper manages to propose a quantitative decision-making model for emergency response to oil spill from ships. The main objective is 1) to identify the influencing factors according to the characteristics of oil spill accidents from ships, 2) to establish a decision-making framework for oil spill from ships, and 3) integrate all the influencing factors and select the best initial response action. The remainder of this paper is organized as follows. Section 2 proposes the decision-making model for oil spill accidents from ships, where the influencing factors are identified and quantified from previous studies. Section 3 applies this proposed decision-making model for a real oil spill accident. Discussion is carried out in Section 4 and conclusions are drawn in Section 5.

## 2 Development of quantitative decision-making model for oil spill accidents

### *2.1 Establish a generic decision-making framework for oil spill accidents*

The decision-making for oil spill from ships is a typical multiple attribute decision-making (MADM) problem. Without loss of generality, $X=\{x_1,x_2,\ldots,x_t\}(t\geq 2)$ is defined as a set of alternatives for emergency response to oil spill from ships. $Y=(y_1,y_2,\ldots,y_s)$ is defined as a set of attributes. Let $A=(a_{ij})_{s\times t}$ be the decision matrix, where $a_{ij}$ is the attribute value. $w_i=(w_1,w_2,\ldots,w_s)$ are the weights of the attributes, such that the weight should be greater than zero and the summation of weights should be equal to 1, which are written as $w_i\geq 0$ $(i=1,2,\ldots,s)$ and $\sum_{i=1}^{s}w_i\geq 0$. Define $V_j(w)$ as the overall assessment on the *j-th* alternative such that the greater value $V_j(w)$ is, the better the *j-th* alternative is.

In order to obtain the overall assessment on the multiple alternatives, the generic decision framework is established. First, the influencing factors and attributes are identified from existing researches and expert experiences, by transforming the influencing factors into evaluation grades of attributes and introducing evidential reasoning algorithm, the decision matrix can be obtained. Second, the attribute values can be determined by using the group belief structure. Last, the final decision-making can be carried out by introducing utility value after the derivation of both decision matrix and attribute weights. The detailed description and expiations of this process is introduced in the following subsections.

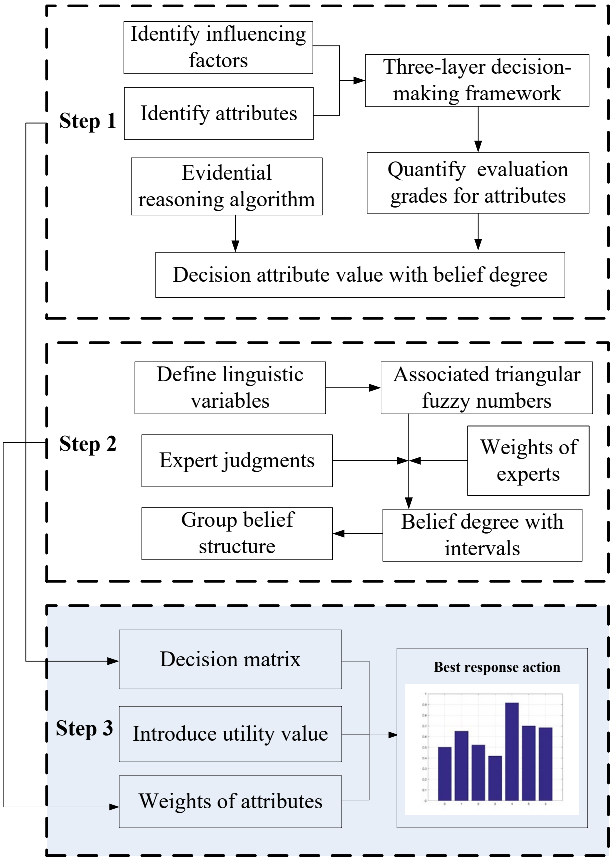


Fig. 1 Generic decision-making framework for oil spill from ships

### *2.2 Identify alternatives and influencing factors of oil spill accidents*

According to (Li et al., 2016; Ventikos, 2004; Xiong et al., 2015), three types of response actions to oil spill from ships are the most common. Specifically, they are physical/mechanical technologies, chemical technologies and biological technologies. However, the biological technology, which has been used in the Exxon Valdez oil spill accidents (Bragg et al., 1994), has a significant impact on the indigenous microorganism communities and it should be carefully handled in practice. Moreover, the manual recovery is used in a remote area for oil spill with small size. It should be carefully handled since its harm to operators (Fingas, 2010). Therefore, as these two alternatives are only used in specific scenarios owing to the potential harmful to environment or people, this paper will not take them into consideration.

Another widely used response actions are skimmer, sorbents, in-stir burning, dispersants (Dave and Ghaly, 2011). It should be mentioned that the boom is not considered because almost all these four alternatives have to use a boom to control the spilled oil. The principle and detailed descriptions are as follows. Skimmer (A1), this alternative removes the spilled oil from the water surface by using mechanical method. Sorbets (A2), this alternative uses the sorbet materials to clean up the traces of spilled oil in water. In-situ burning (A3), this alternative removes the spilled oil by burning it in the accidental scene. Dispersant (A4), this alternative is a chemical technology and it removes oil by breaking it into small droplets.

The different alternatives may be influenced by multiple factors and be used for emergency response to oil spill from ships in specific conditions. For example, sorbets can only be used for small spills (Bayat et al., 2005; Fingas, 2010), while the slicks must be about 0.5 to 3.0 mm thick to start a burn and about 1.0 mm thick to stop the burn (Fingas, 2012). Therefore, in order to select the best alternative in response to oil spill from ships, the influencing factors should be identified from the literature. They are the oil viscosity (Dave and Ghaly, 2011; Ventikos, 2004), oil thickness (Li et al., 2016), spill size (Montewka et al., 2013; Vanem et al., 2008), oil type (Dave and Ghaly, 2011; Montewka et al., 2013), wave height (Montewka et al., 2013; Ventikos, 2004), sea type (Li et al., 2016), sensitive area such as the water intake (Wu et al., 2015), cleanup cost (Dave and Ghaly, 2011; Montewka et al., 2013; Vanem et al., 2008), wind velocity (Ventikos, 2004), water temperature (Li et al., 2016), current velocity (Ventikos, 2004), emergency resources (Dave and Ghaly, 2011; Montewka et al., 2013; Xiong et al., 2015), recovery rate (Dave and Ghaly, 2011).

Similar with Wu et al. (2016), if all the influencing factors are included as the attributes, there will be too many attributes and it will make the experts (who are invited to make assessment to obtain the weights of attributes) confused. Therefore, the three-level decision-making framework is established and is shown in Fig. 2. In this framework, the first level is indicated as the level for reference, the second level is indicated as the level for attributes, while the third level is indicated as the level for influencing factors. In this framework, we denote

$Z=(z_1, z_2, \ldots, z_r)$ as the influencing factors and $w=\{w_k^i, k=1,2,\ldots,r\}$ as the weights of the influencing factors, where $0 \le w_j^i \le 1$ and $\sum_{k=1}^{r} w_k^i = 1$.

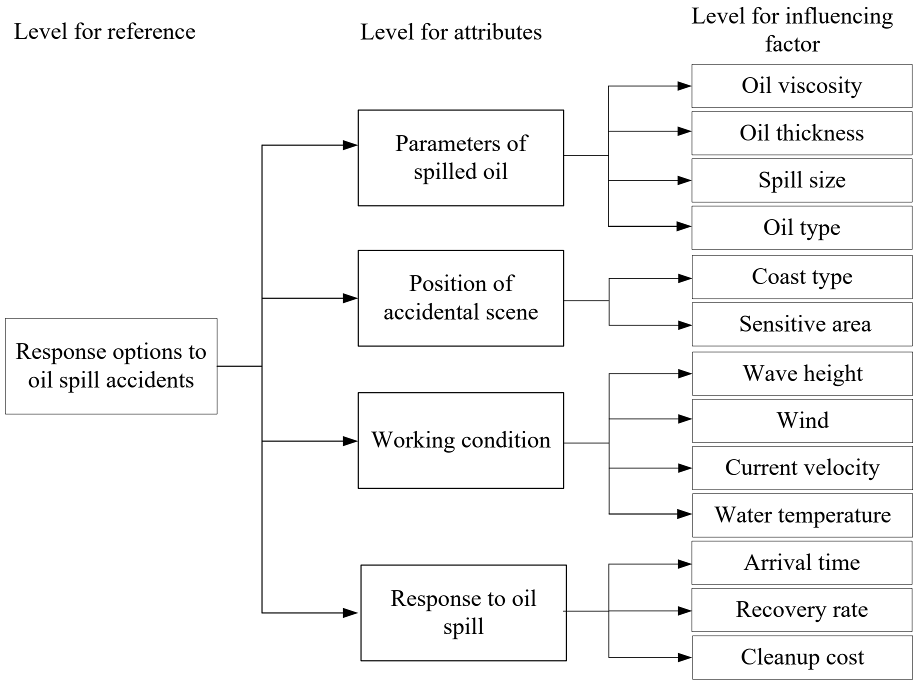


Fig. 2 Three-layer decision-making framework for oil spill from ships

### *2.3 Quantify the evaluation grades of the influencing factors*

The quantification of the evaluation grades is the most significant step, as there are only few historical data, which means it is hard to establish a data-driven model. Two steps achieve this in the decision-making process.

The first step is to define the number of evaluation grades. To define the number of evaluation grades is hard because if there are too many evaluation grades, the experts will be confused to make judgments since the expert judgments are introduced to define the number of evaluation grades (Wu et al., 2016; Montewka et al., 2013). However, if there are only few evaluation grades, the result may not be convincing (Wu et al., 2017c; Fu et al., 2016). Therefore, more than three and fewer than seven evaluation grades were considered in previous studies, and five grades are used in this paper.

The second step is to quantify the evaluation grades. When using fuzzy logic method, the quantification of evaluation grades rely on expert judgments (Wu et al., 2016), while using the Bayesian network, both expert judgments and historical data has been introduced in Wu et al. (2017c) and Fu et al. (2016). However, the expert judgments are not always reliable, as the subjective judgments may be influenced by many factors such as the knowledge, age and background. In this paper, these evaluation grades and associated values are obtained from previous studies, because they have already been verified in previous research.

Suppose $H^k$ is a set of evaluation grades for the $k$ -th influencing factor, which can be written as $H^k = H_{n,k}, n = 1,2,\dots,N_k$ .Then, the assessment can be represented as $S(b_k^i(j)) = \{H_{n,k}, \gamma_{n,k}^i(j)\} \quad n = 1,2,\dots,N_k$ . Where $\gamma_{n,k}^i(j) \geq 0$ and $\sum_{n=1}^{N_k} \gamma_{n,k}^i(j)=1$ . The evaluation grades and the associated values for sorbents (A2) are shown in Table 1. Meanwhile, references to define the Influencing Factors and quantify the five evaluation grades are cited in Table 1.

Table 1. Evaluation grades for the influencing factors of oil spill from ships （A2 Sorbents example）

| Influencing Factors | Very bad | Bad | Normal | Good | Very good | References |
|---|---|---|---|---|---|---|
| oil viscosity [cst] | below 0.5k | 0.5k~1k | 1k~1.5k | 1.5k~2k | above 2k | (Li et al., 2016) |
| oil thickness [mm] | 6~10 | 3~6 | 1~3 | 0.5~1 | below 0.5 | (Zhong and You, 2011) |
| spill size [km$^2$] | 2k~3k | 1k~2k | 0.5~1k | 0.1~0.5 | below 0.1 | (Xiong et al., 2015) |
| oil type | - | - | $E_1$ | $E_2$ | $E_3$ | (Garrett et al., 2017) |
| coast type | - | - | $F_1$ | $F_2$ | $F_3$ | (Lan et al., 2015) |
| sensitive area [nm] | below 0.25 | 0.25~0.5 | 0.5~1 | 1~2 | 2~3 | (Lan et al., 2015) |
| wave height [m] | 1.2~1.5 | 1~1.2 | 0.5~1 | 0.25~0.5 | below 0.25 | (Montewka et al., 2013) |
| wind [Beaufort scale] | above 6 | 4~6 | 2~4 | 1~2 | below 1 | (Kang et al., 2016) |
| current velocity [kn] | 2~2.5 | 1.5~2 | 1~1.5 | 0.5~1 | below 0.5 | (Montewka et al., 2013) |
| water temperature [°C] | -2~0 | 0~3 | 3~10 | 10~20 | 20~30 | (Sayed and Zayed, 2006) |
| arrival time [h] | 4~5 | 3~4 | 2~3 | 1~2 | 0~1 | (Xiong et al., 2015) |
| recovery rate [%] | 0~20 | 20~40 | 40~70 | 70~90 | 90~100 | (Li et al., 2016) |
| cleanup cost [$] | 10k~23k | 5k~10k | 3k~5k | 1k~3k | below 1k | (Li et al., 2016) |

It should be mentioned in Table 1 that the two qualitative influencing factors, which are oil type and coast type, uses the linguistic terms rather than numerical data for quantification. Specifically, $(E_1, E_2, E_3)$ , the linguistic terms for oil type, stands for weathered spilled oils, light oil and heavy oil, respectively, while $(F_1, F_2, F_3)$ , the linguistic terms for coast type, stands for open sea, inland waterways, and shoreline, respectively. Another thing should be mentioned is that the quantification of the evaluation grades for the different alternatives is different. This is because the different influencing factors have different impact on the alternatives. For example, the sorbents are suitable for the small oil spills (Fingas, 2010), while the in-situ burning is suitable for the large spill size. This is the similar with the decision-making model for not under control ships (Wu et al., 2016), while we quantified the evaluation grades differently.

### *2.4 Use of evidential reasoning to integrate the influencing factors*

Evidential reasoning method, proposed by (Yang and Xu, 2002), is widely used for maritime transportation in previous studies (Wu et al., 2017a; Zhang et al., 2016). Compared with fuzzy logic and Bayesian network, the merits of the evidential reasoning method are that it can integrate multiple influencing factors by its own algorithm (Wu et al., 2017a) and do not need to establish many reasoning rules in the modelling process. For example, the decision-maker have to establish 625 ( $5\times5\times5\times5$ , four input variables and each with five evaluation grades) IF-THEN rules for the parameters of spilled oil, which will make the decision-maker confused since the decision-maker have to also establish IF-THEN rules for other three attributes. Moreover, the decision-maker has to establish lots of extended IF-THEN rules to obtain the conditional probability tables (CPTs) because few historical data are available to achieve the CPTs in this case (Wu et al., 2017c).

The influencing factors are integrated as following. Define the $E^i_{L(k)}$ as a subset of the $i$ -th attribute, which consists of the k-th influencing factors. Then, in the evidential reasoning algorithm (Yang and Xu, 2002), the remaining probability mass, unassigned to individual grades after all the influencing factors in $E^i_{L(k)}$ have been assessed, are divided into two parts: one is caused by weights, which is written as $M^i_{H,k}$ ; the other is caused by the uncertainty of the *k*-th influencing factors, which is written as $m^i_{H,k}$ , and the summation of the uncertainty is defined as $G^i_{H,j} = M^i_{H,j} + m^i_{H,j}$ . Let $m^i_{n,k}$ be the basic probability mass of the $k$ -th influencing factors, which represents to how many degrees this influencing factor supports the hypothesis that the criterion is assigned to the $n$ -th grade $H_n$ .

$$m^i_{n,k} = w^i_k \beta^i_{n,k}(j) \tag{1}$$

$$M^i_{H,k} = 1 - w^i_k \tag{2}$$

$$m^i_{H,k} = w^i_k (1 - \sum_{n=1}^{N} \beta^i_{n,k}(j)) \tag{3}$$

$$\{H_n\}: m^i_{n,L(k+1)} = C^i_{n,L(k+1)}(m^i_{n,L(k)}m^i_{n,k+1} + m^i_{H,L(k)}m^i_{n,k+1} + m^i_{n,L(k)}m^i_{H,k+1}) \tag{4}$$

$$G^i_{H,L(k)} = M^i_{H,L(k)} + m^i_{H,L(k)} \tag{5}$$

$$\{H\}: M^i_{H,L(k+1)} = C^i_{n,L(k+1)}(M^i_{H,L(k)}M^i_{H,k+1} + M^i_{H,L(k)}M^i_{H,k+1} + M^i_{H,L(k)}M^i_{H,k+1}) \tag{6}$$

$$C^i_{n,L(k+1)} = \left[1 - \sum_{u=1}^{N}\sum_{v=1}^{N} m^i_{u,L(k)}m^i_{v,k+1}\right]^{-1} \tag{7}$$

Moreover, the uncertainty caused by the weights is reassigned to the individual grades proportionally (Yang and Xu, 2002).

$$\{H_n\}: \beta^i_{n,k}(j) = \frac{m^i_{n,L(r)}}{1 - m^i_{H,L(r)}} \tag{8}$$

$$\{H\}: \beta^i_H(j) = \frac{M^i_{n,L(r)}}{1 - m^i_{H,L(r)}} \tag{9}$$

### *2.5 Derive the weights of attributes using linguistic variables*

The weights of the attributes, which represents of the importance of the attributes, are derived from the expert judgements from previous works (Wu et al., 2016; Wu et al., 2017b). In order to obtain reasonable weights of the attributes, the research group have invited four experts to solve this problem. It is discovered that the experts prefer to use linguistic variables to express the importance of weights, for example, the experts use the terms such as "important" and "unimportant" to express the attributes. Therefore, in order to make a comprehensive consideration of the opinions of all experts, the linguistic terms should be defined, this is achieved by using the following three steps.

First, the linguistic terms, which are used to express the importance of the attributes, should be defined. Traditionally, the linguistic terms are defined to be more than three and less than seven from previous studies (Pam et al., 2013; Alyami et al., 2016). The reason is that if the linguistic terms are less than three, it is difficult to distinguish which attribute is more important than others. Moreover, if the linguistic terms are more than seven, the experts are hard to choose an appropriate linguistic term to express the slight difference between two adjacent terms. Therefore, five linguistic terms, which are "very unimportant (VU)", "unimportant (U)", "normal (N)", "important (I)", "very important (VI)", are used in this paper.

Second, the triangular membership function is used to quantify the linguistic variables. In order to transform the linguistic variables to numerical values, the membership function is introduced in this paper. The triangular and rectangle membership function are the most widely methods (Wu et al., 2016; Liu et al., 2013). In this paper, in order to simplify this process, the triangular membership functions are utilized, moreover, the linguistic terms and associated triangular fuzzy numbers are defined and shown in Table 2, which is proposed by Liu et al. (2013). Assume $p$ experts are invited to make judgements, and the weights of the experts is defined as $\lambda_p$, where the summation of the weights is equal to 1. The judgments are defined as $f_i^{mp} = (f_{il}^{mp}, f_{i2}^{mp}, f_{i3}^{mp})$, where $f_i^{mp}$ as the $m$-th ($m = 1,2,3,4,5$) membership function given by the $p$-th ($p = 1,2,3,4$) expert.

Table 2. Linguistic terms and associated triangular fuzzy numbers

| Linguistic terms | triangular fuzzy numbers |
|---|---|
| very unimportant (VU) | (0,0,0.25) |
| unimportant (U) | (0,0.25,0.5) |
| normal (N) | (0.25,0.5,0.75) |
| important (I) | (0.5,0.75,1) |
| very important (VI) | (0.75,1,1) |

Third, the expert judgments should be integrated. This process can be achieved in three steps.

① The expert judgments on the same evaluation grades ($n$-th) is first integrated by multiply the associated weights of the experts.

$$w_i^m = (\sum_{p=1}^{4} \lambda_p f_{i1}^{mp}, \sum_{p=1}^{4} \lambda_2 f_{i2}^{mp}, \sum_{p=1}^{4} \lambda_p f_{i3}^{mp}) \tag{10}$$

② The triangular fuzzy numbers are transformed to the associated numerical numbers using Table 2.

$$w_i = (\sum_{n=1}^{5} \sum_{p=1}^{4} \lambda_p f_{i1}^{mp}, \sum_{n=1}^{5} \sum_{p=1}^{4} \lambda_2 f_{i2}^{mp}, \sum_{n=1}^{5} \sum_{p=1}^{4} \lambda_p f_{i3}^{mp}) \tag{11}$$

③ Finally, the weights of the attributes are obtained by calculating the mean value using Eq. (12).

$$w_i = \frac{\sum_{n=1}^{5}\sum_{p=1}^{4}\lambda_p f_{i1}^{mp}, \sum_{n=1}^{5}\sum_{p=1}^{4}\lambda_2 f_{i2}^{mp}, \sum_{n=1}^{5}\sum_{p=1}^{4}\lambda_p f_{i3}^{mp}}{3} \tag{12}$$

### *2.6 Introduce utility value for final decision-making*

The utility value is introduced for final decision-making. Suppose $u(H_n)$ is the utility of the grade $H_n$, then, the final utility can be obtained by multiply the integrated value in Section 2.4 by the utility value, it can be seen that the greater value of $u(V_{ij})$, the better alternative is.

$$u(V_{ij}) = \sum_{n=1}^{5} \beta_n^i(j) u(H_n) \tag{13}$$

## 3 Application of the proposed model for oil spill accidents

### *3.1 Scenario description of oil spill accident*

The proposed model is applied to select the best response options to oil spill from ships. The oil spill accident occurred in the No. 31 buoy of Guangzhou in 2010, and its precise position is (22°00′N, 114°30′E). The tanker first collided with another ship and this caused a secondary accident, which is an oil spill accident. At that time, the wind was from 3 to 4 (Beaufort scale), the velocity of current was from 0.7 to 1.5 kn, the water temperature was from 24.1 to 29.1 °C. After collision, the tanker sank and the oil spill size was 230 $m^3$, while the oil type was heavy oil. Oil viscosity was 1000 to 2000cst, the oil thickness was 0.9 to 1.3 mm. As the accident occurred in the fairway, the skimmers were estimated to arrive at the accidental scene within 3.5 hours; the sorbets were estimated to arrive within 2.3 hours, the dispersants were estimated to arrive within 1.6 hours, and the oil was estimated to burn up in 2.6 hours. Specifically, the detailed information of this oil spill accident is shown in Table 3. However, it should be mentioned that the cleanup cost is obtained from (Li et al., 2016), specifically, the in-situ burning is \$3127.87 per tonne, dispersants is \$5633.78 per tonne, mechanical is \$9611.9 per tonne and manual is \$23403.45 per tonne, which are all shown in Table 3.

**Table 3. Detailed information of influencing factors for oil spill accident**

| No. | Influencing factors | Information |
|---|---|---|
| 1 | Oil viscosity [cst] | 1k~2k |
| 2 | Oil thickness [mm] | 0.9~1.3 |
| 3 | Oil spill size [$km^2$] | 230 |
| 4 | Oil type | Heavy oil |

| | | |
|---|---|---|
| 5 | Sea state [m] | 1.0~1.5 |
| 6 | Wind [m/s] | 3.4~7.9 |
| 7 | Current velocity [kn] | 0.7~1.5 |
| 8 | Water temperature [°C] | 24.1~29.1 |
| 9 | Coast type | Open sea |
| 10 | Distance to sensitive area [n mile] | 2.8 |
| 11 | Estimated arrival time of emergency resources [h] | (3.5,2.3,1.6,2.6) |
| 12 | Recovery rate [%] | 10%~98% |
| 13 | Cleanup cost [$] | (9611.9, 9611.9, 3127.87, 5633.78) |

### *3.2 Assessment of the influencing factors for oil spill from ships*

The influencing factors of this oil spill accident can be assessed by using the evaluation grades shown in Table 1. It should be mentioned that there are two types of information in this scenario, which are quantitative and qualitative information. For the quantitative information, this method only has to calculate the geometric distance and the proportion of this distance is assigned to the corresponding linguistic variables (Wu et al., 2017b). Take the oil spill size of the skimmer (A1) for example, and it can be assessed by using the following equations.

$$\begin{cases} \beta_{4,1} = \dfrac{H_4 - \delta_3}{H_5 - H_4} = \dfrac{500-230}{500-100} = 0.675 \\ \beta_{5,1} = \dfrac{\delta_3 - H_5}{H_5 - H_4} = \dfrac{230-100}{500-100} = 0.325 \end{cases}$$

Then, the assessment can be easily obtained.

$$S(b_3^1) = \{(H_1,0),(H_2,0),(H_3,0),(H_4,0.675),(H_5,0.325)\}$$

However, for the qualitative information, there are two steps to achieve this.

First, the transformation matrix is introduced to transform the qualitative information to the evaluation grades. Take the coast type of the skimmer (A1) as an example, the transformation matrix is established as follows.

$$P_4 = (E_{jn})_{3\times 5} = \begin{pmatrix} 0 & 0 & 0.8 & 0.2 & 0 \\ 0 & 0 & 0 & 0.7 & 0.3 \\ 0 & 0 & 0 & 0.1 & 0.9 \end{pmatrix}$$

Then, the assessment can be obtained.

$$S(b_9^1) = \{(H_1,0),(H_2,0),(H_3,0),(H_4,0.7),(H_5,0.3)\}$$

### *3.3 Derivation of the decision matrix after integration of influencing factors*

The decision matrix is obtained by using evidential reasoning algorithm to integrate the influencing factors. In this process, the weights of the influencing factors should be first defined. In this paper, the influencing factors with the same attribute is treated equally. For example, the “oil viscosity”, “oil thickness”, “oil spill size” and “oil type” are assumed as equal importance (the weight is 0.25) as they belong to the same attribute “parameter of spilled oil”. This treatment is carried out owing to two reasons. First, as the influencing factors belong to the same attribute, they should have some common features which makes them all important, otherwise, they must have been excluded from the influencing factors. Second, it is very hard to distinguish the importance of these influencing factors. Traditionally, the weights of them are obtained from expert judgements, it will confuse the experts to judge the influencing factors, if there are so many influencing factors.

After defining the weights of the attributes, the attribute value can be obtained by using the evidential reasoning algorithm, which is described in detail in Subsection 2.4. However, a simple way to accomplish this is to use the IDS software, which is developed by Yang (2001) and is available from www.e-ids.co.uk. In this software, the user only has to define the hierarchical structure of the decision-making model, which is shown in Fig. 3. Moreover, the evaluation grades of the qualitative and quantitative should also be defined in this software, and the result of the attribute value can be obtained. It should be mentioned that as the quantification of the influencing factors with different alternatives is different, four such hierarchical structures should be established in order to define the evaluation grades in different alternatives.

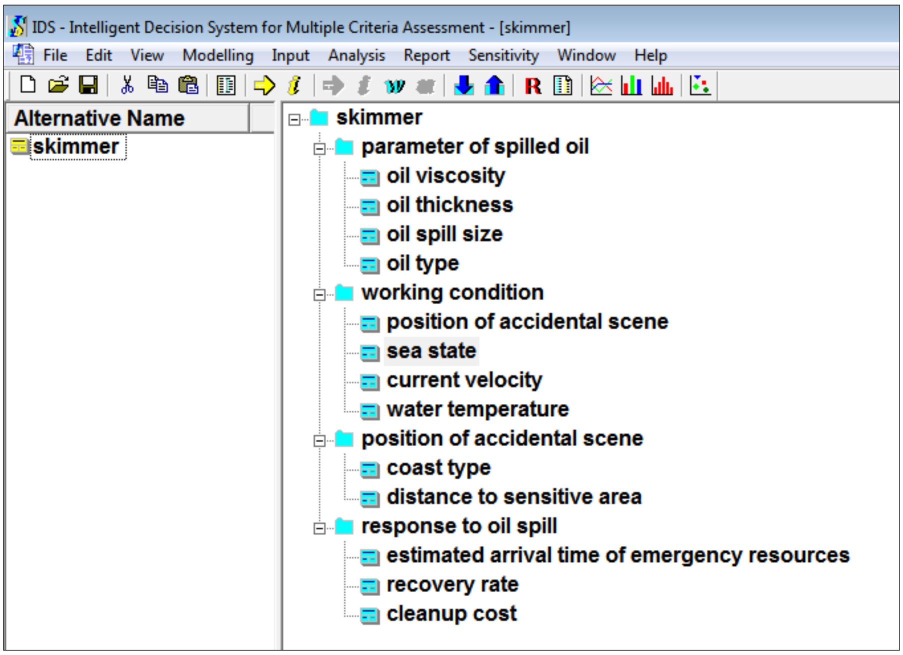


Fig. 3 Hierarchical decision-making structures for skimmer using IDS software

Afterwards, the attribute value of each alternative can be obtained by using this software. Take the parameter of spilled oil as an example, the attribute value of parameter of spilled oil can be expressed as $a_{11} = \{(H_1,0),(H_2,0.3023),(H_3,0.0227),(H_4,0.2065),(H_5,0.4685)\}$. In this IDS software, it can be easily derived and shown in Fig. 3. Similarly, the other attribute value can also be obtained. Specifically, the attribute value of position of accidental scene, working conditions and response to oil spill can be expressed as follows.

$$a_{21} = \{(H_1,0),(H_2,0),(H_3,0),(H_4,0.1642),(H_5,0.8358)\}$$

$$a_{31} = \{(H_1,0),(H_2,0.3372),(H_3,0.4378),(H_4,0.1238),(H_5,0.1013)\}$$

$$a_{41} = \{(H_1,0),(H_2,0.4906),(H_3,0.3313),(H_4,0.1781),(H_5,0)\}$$

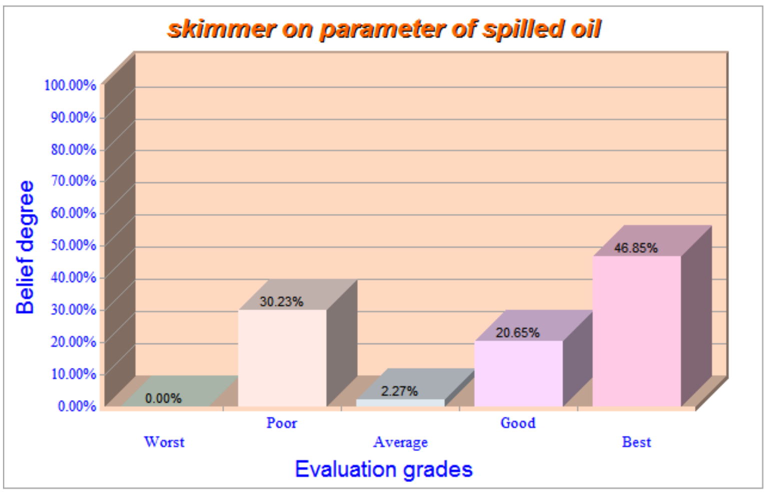


Fig. 4 Attribute value of the parameters of spilled oil (skimmer example)

As the evaluation grades for different alternatives are different, the assessment on the other alternatives should also be calculated. They can also be carried out by using the IDS software, and the result for the different alternatives, which is the decision matrix, is shown in Table 4. It should be mentioned that the decision attribute matrix is expressed by the belief degree of the evaluation grades rather than the numerical values, this is because it is obtained by integrating the influencing factors. However, the final utility value is obtained after a second round integration of the decision attributes using evidential reasoning algorithm and a transformation of the utility value, and this will be carried out in the following subsection.

Table 4. Decision attribute matrix of the oil spill accidents

| alternative | Decision attribute | $(H_1, H_2, H_3, H_4, H_5)$ |
|---|---|---|
| Skimmer (A1) | parameter of spilled oil | $(0, 0.302, 0.022, 0.206, 0.468)$ |
| | position of accidental scene | $(0, 0, 0, 0.164, 0.836)$ |
| | working condition | $(0, 0.337, 0.434, 0.124, 0.101)$ |
| | response to oil spill | $(0, 0.491, 0.331, 0.178, 0)$ |
| Sorbets (A2) | parameter of spilled oil | $(0, 0, 0.258, 0.366, 0.376)$ |
| | position of accidental scene | $(0, 0, 0, 0.164, 0.836)$ |
| | working condition | $(0.415, 0.469, 0, 0.363, 0.127)$ |
| | response to oil spill | $(0, 0.331, 0.453, 0.217, 0)$ |
| In-situ burning (A3) | parameter of spilled oil | $(0.562, 0.218, 0.220, 0, 0)$ |
| | position of accidental scene | $(0.2, 0.3, 0.1, 0.4, 0)$ |
| | working condition | $(0, 0.919, 0.127, 0.547, 0.234)$ |
| | response to oil spill | $(0, 0, 0.190, 0.670, 0.139)$ |
| Dispersants (A4) | parameter of spilled oil | $(0.270, 0.229, 0.143, 0.359, 0)$ |
| | position of accidental scene | $(0.189, 0.434, 0.377, 0, 0)$ |
| | working condition | $(0.023, 0.479, 0.231, 0.267, 0)$ |
| | response to oil spill | $(0, 0039, 0.267, 0.462, 0.232)$ |

It can be seen from Table 5 that the different alternatives have their advantage and also disadvantage for response to oil spill from ships. For the parameter of spilled oil, the sorbets alternative is better than other alternatives. However, the in-situ burning is the worst as the oil is too thin (only 1.5 mm) to burn and from Li et al. (2016), the oil must be about 0.5 to 3.0 mm thick to start a burn and about 1.0 mm thick to stop the burning. Moreover, the spill size is also not large enough to burn. For the position of the accidental scene, the sorbets and skimmer are the same and better than other alternatives, while the dispersant is the worst. This is because the mechanical recovery is often used for the oil spill in the fairway while the dispersants will influence the environment since the Chinese White Dolphin lives around this waterway area. For the working condition, the in-situ burning is the best because this navigational environment (including the sea state and wind) will not influence the oil burning but will influence the mechanical recovery, therefore, use of the sorbets is the worst. While for the last attribute, response to oil spill, use of the dispersants is the best because of the high recovery rate the short arrival time, however, the skimmer is the worst because the relatively low recovery rate, high cost and long arrival time (Li et al., 2016).

Moreover, it can also be discovered from Table 4 that the different alternatives have their own advantages and disadvantages for this oil spill accident. In order to make a comprehensive assessment on these alternatives, the importance of these attributes should be considered. However, it should be mentioned that the influencing factors are treated equal importance while the weights of attributes are treated differently; this different treatment is owing to two reasons. First, the attributes are different in nature and may significantly influence the result, but the influencing factors belong to the same attribute and they should have similar influence on the same attribute. Second, as the weights of the attributes have been treated differently in this paper, and the importance of the associated influencing factors have been considered in this step. If the weights of the influencing factors have also been considered, their importance would have considered twice. Moreover, this paper discusses the results when treating the importance of the attributes equally and unequally, which will make the result clear ad reasonable.

### *3.4 Subjective judgments on the importance of decision attributes*

As the weights of the attributes are important for selection of the best alternative and derived from expert judgments, an interview has been carried out in order to obtain a comprehensive result of the weights. Four experts have been invited to attend this interview. Their detailed information is shown in Table 5.

Table 5 Detailed information of the invited four experts

| No. | Institution | Age [Years] | Experience [Years] | Type of experience | Gender |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Expert 1 | MSA | 41 | 10 | He has worked as an officer in MSA to control maritime safety in Guangdong waterway area and has successfully handled more than 200 maritime accidents. | male |
| Expert 2 | Manager | 48 | 15 | He works as the manager in the dangerous cargo wharf and in charge of the marine pollution according to the emergency preparedness plan | male |
| Expert 3 | Ocean-going ships | 40 | 15 | He works as a captain in merchant ships, and has once experienced oil spill accidents in the Guangdong waterway area | male |
| Expert 4 | University | 51 | 22 | He was a chief officer in the ocean-going ship and teaches the marine pollution prevention in a university. | male |

As mentioned before, the four experts prefer to use the linguistic terms to express their assessment on the weights, and their judgements are shown in Table 6. Moreover, as their different background, knowledge, etc., the weights of the experts are given a predefined value $w_n = (0.3, 0.3, 0.2, 0.2)$. It can be seen that the MSA officer and the manager are assigned a greater value than the captain and the professor, this is because the MSA officer and manager have more experience on how to response to the oil spill accidents from a comprehensive way. However, the captain and the professor have only worked as seafarers on the ship and may consider the response to oil spill accidents only from the crew's perspective.

Table 6 weights of the experts and their judgments

| Decision attribute | Expert No. and weights | Expert judgments using linguistic variables |
|---|---|---|
| parameter of spilled oil | Expert 1 (0.3) | Important |
| | Expert 2 (0.3) | Very important |
| | Expert 3 (0.2) | Normal |
| | Expert 4 (0.2) | Normal |
| position of accidental scene | Expert 1 (0.3) | Very important |
| | Expert 2 (0.3) | Normal |
| | Expert 3 (0.2) | Important |
| | Expert 4 (0.2) | Normal |
| working condition | Expert 1 (0.3) | Normal |
| | Expert 2 (0.3) | Important |
| | Expert 3 (0.2) | Unimportant |
| | Expert 4 (0.2) | Normal |
| response to oil spill | Expert 1 (0.3) | Unimportant |
| | Expert 2 (0.3) | Normal |
| | Expert 3 (0.2) | Normal |
| | Expert 4 (0.2) | Important |

By using Eqs. (10) - (11), the numerical numbers of each decision attribute can be obtained. Take the parameter of spilled oil for example. First, the linguistic terms are transformed to the numerical values by using Table 1, and the judgments of the Expert 1 is transformed to (0.5,0.75,1). Second, the weights of the experts should be considered, and the weighted judgments of the Expert 1 is (0.15,0.225,0.3). Last, all the experts judgments are summarized by using Eq. (11), and the judgment of parameter of spilled oil and other decision attributes are:

$f_1 = (0.475, 0.725, 0.900)$

$f_2 = (0.450, 0.700, 0.857)$

$f_3 = (0.275, 0.525, 0.775)$

$f_4 = (0.225, 0.475, 0.725)$

Finally, the weights of the decision attribute can be calculated by using Eq. (12), which is $w_i = (0.296, 0.282, 0.222, 0.200)$. It can be seen that the parameter of spilled oil is the most important as it will significantly influence whether this response alternative is useful or not. The position of accidental scene is also important as this response alternative can be used or not. The response to oil spill is assumed to be not so important not only because the cost is not the first thing should be considered in emergency response but also the recovery rate is close to each other for all the response actions and with only small differences. However, it should be mentioned that all these attributes are important but with slight difference as their weights are all greater than 0.2.

### *3.5 Selection of the best alternative for oil spill accident*

After integrating the linguistic variables of the expert judgments, the evidential reasoning algorithm is used twice to integrate the decision attributes. This process can also be carried out by using IDS software. The result of the skimmer is shown in Fig. 5.

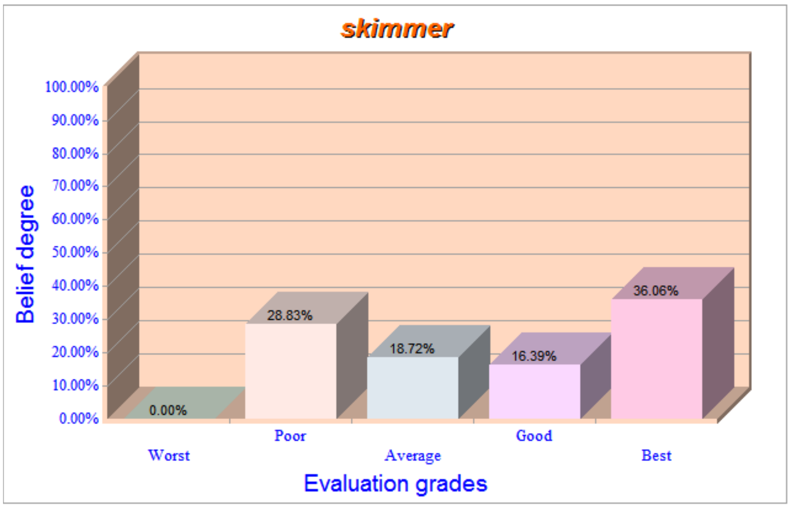

Fig. 5 Assessment on the skimmer alternative

Similarly, the assessment on the other alternatives can be derived, and all the assessments can be represented as follows.

$\beta_n^1 = \{(H_1,0),(H_2,0.288),(H_3,0.187),(H_4,0.164),(H_5,0.361)\}$

$\beta_n^2 = \{(H_1,0.011),(H_2,0.189),(H_3,0.157),(H_4,0.305),(H_5,0.339)\}$

$\beta_n^3 = \{(H_1,0.207),(H_2,0.154),(H_3,0.159),(H_4,0.392),(H_5,0.088)\}$

$\beta_n^4 = \{(H_1,0.122),(H_2,0.318),(H_3,0.243),(H_4,0.278),(H_5,0.039)\}$

As the assessment on the alternatives are expressed by evaluation grades, the utility value of the evaluation grades should be defined. In this paper, the same utility value of each evaluation grades are defined as the same with (Yang and Xu, 2002). Specifically, they are defined as follows.

$$u("VU") = u("H_1")=0$$

$$u("U")=u(H_2) = 0.35$$

$$u("N")=u(H_3) = 0.55,$$

$$u("I")=u(H_4) = 0.85$$

$$u("VI")=u(H_5) = 1$$

By introducing these utility values, the decision matrix of different attributes can be obtained and shown in Table 7.

Table 7 final decision of the response actions to oil spill accidents

| alternative | utility | Ranking |
|---|---|---|
| A1 | 0.704 | 2 |
| A2 | 0.750 | 1 |
| A3 | 0.563 | 3 |
| A4 | 0.520 | 4 |

It can be seen from Table 7 that the best alternative for this oil spill accident is the sorbets. This is owing to two reasons. First, using the sorbets is the best alternative because it is better for this oil spill accident not only because of the parameters of spilled but also the position of accidental scene from the analysis of Table 5 (Table 7?). Second, the weights of these two attributes are also more important than other two attributes from the expert judgments. Moreover, the skimmer ranks second because the position of accidental scene is also suitable for using skimmer. Use of the dispersant is the last choice because this option will significantly influence the Chinese white Dolphin.

## 4 Discussion

As the response to oil spill from ships is limited in time, the time-consuming by using this decision-making method should be discussed. In this decision-making process, the decision-maker has to 1) input the prior information for the accident scenario, 2) invite multiple experts to make judgments on the attributes using linguistic variables. The first step is very simple because the hierarchical decision-making framework has been established and the influencing factors have been quantified, specifically, this step takes around 30 seconds. However, the second step is much more time-consuming owing to the following reasons. First, there are multiple experts (usually at least three, this case study is four) are invited to make judgments although they can make judgments simultaneously. Second, the experts may prefer different quantification standards. For example, some expert may prefer use three linguistic variables (i.e. important, normal, unimportant) than make judgments, while some may prefer uses five (i.e. the same with this case study) or even more. Therefore, before making judgments, the explanation of these five linguistic terms should be introduced to the experts in order to have the same standards, and this will cost one minute. After making judgments, the weights of the attributes can be quickly obtained and it will only cost around ten seconds. Finally, as the IDS software can be introduced to integrate the influencing factors, the result can be quickly obtained.

The simplification of the proposed model should also be discussed as the derivation of the weights is much time-consuming, which makes the proposed model a little bit complicated. In practice, if the decision-making is urgent and extremely limited in time, the decision-making process can be simplified in two ways. The first way is to use a simple method to derive the weights of attributes. Two methods can also be used to achieve this, the first simple method is to use the analytic hierarchy process (AHP) by comparing the four attributes to obtain the pairwise comparison matrix using a nine-rank scale method, which is widely used to derive the relative importance of the different attributes (Wu et al., 2016; Wu et al., 2017b). By introducing this simple method, the decision-making process will be much quicker than using the linguistic variables as this method has been integrated in the IDS software. However, another simple method is much easier than all these two methods and the decision-maker directly use the numerical numbers to make judgments on the attributes. By introducing this method, the decision-making process is much quicker and the total time-consuming of this process will be less than one minute. The second way to simplify the decision-making model is to reduce the number of experts. As the experts may have different education background, working experience, etc., the judgments given by different experts may be different, and if their assessments are quite different from each other, the experts should be invited to make judgments again, and this process will cost a lot of time. By reducing the number of experts, the decision-making process will be much easier and quicker though this may slightly influence the accuracy of the results.

The weights of the attributes and influencing factors should also be discussed as they are defined in a different way. In this paper, the weights of the influencing factors with the same attribute are assumed to be equal while the weights of the different attributes are derived from expert judgments and they are different from each other. The weights of the influencing factors are defined the same owing to three reasons. First, the emergency response to oil spill from ships is limited in time, if all the weights of influencing factors are defined by using expert judgments such as AHP and the linguistic variables, the consumed time will be close to five times (four attributes needs to make judgments) of the cost time in the proposed model in this paper. This will be unacceptable in emergency response and will make the response actions meaningless. Second, as the weights are derived by using expert judgments, the experts will be confused if they are invited to give judgments on both attributes and influencing factors. Third, only the weights of the influencing factors that assumed to be equal importance belong to the same attribute and this is reasonable because the importance of the attributes has been considered and if the weights of influencing factors has also been taken into consideration, the importance of the influencing factors will be considered twice. Moreover, the weights of the influencing factors are assumed to be the same because they belong to the same attribute. However, it should be mentioned that although in this paper the weights of the influencing factors are assumed to be the same, they can also be easily to be considered in the IDS software if they are derived and given in advance. The weights of the attributes are defined as different from each other owing to two reasons. First, the results are significantly influenced by the weights of the attributes. Second, the weights of the attributes can also be discovered to be different as their importance is different. For example, the response to oil spill is not so important because it includes the cleanup cost and also the recovery rate, in the emergency response, cleanup cost is one of the last things to be considered. Moreover, the recovery rates of the different actions are close to each other, which makes this attribute not so important. However, the parameters of spilled oil and the position of accidental scene should be important, because it significantly influences whether this response action can be used or not.

The last thing should be discussed is that only the initial response action is considered in this study, while the combined action (such as using both skimmer and sorbets) is not considered. This is reasonable as this proposed decision-making model focuses on the oil spill from ships, while the oil spill caused by offshore drilling platform and others are not considered. It should be modified when applying it to other types of oil spill accidents as the oil spill from ships owns distinguishing features. First, the oil spill size caused by ships is relatively small, which means the required emergency resources are small. Therefore, the oil spill from ships does not need combined actions. Second, as the oil spill from ships often occurs in the fairway and it may influence the passing by ships, the response actions should be quick. This means it is hard to take enough time to think out a perfect response action but a reasonable action that can effectively control the oil spill accidents. Third, from the historical oil spills from ships (around 10 cases) and expert experience, the initial response action is assumed to be the most important and can effectively control the oil spill in the majority of the oil spill accidents (90%) caused by ships.

## 5 Concluding remarks

The main contribution of this paper is to propose a quantitative decision-making model for emergency response to oil spill from ships. Although almost all the influencing factors and response actions have been analyzed in previous works, but none of them have given a comprehensive and quantitative solution for oil spill from ships, while this paper proposes a three-layer decision framework to take all these influencing factors into consideration. Another merit of the comprehensive and quantitative solution for oil spill accidents is that it provides a quick screening method of the multiple alternatives, which is extremely useful for response to oil spill from ships owing to time limitation. Moreover, as the experts may prefer to use linguistic variables to express the importance of the decision attributes, this paper also introduces a quantitative method to integrate the different linguistic variables. From the result of the case study, the proposed method is practical and useful for response to oil spill from ships, and it can be applied to another oil spill from ships in different waterway areas.

It should be mentioned that the decision-making model is established and quantified with the reference of previous research. Although the result of this case study is the same with reality by introducing the model, more cases should be introduced to verify the proposed model in the future because some oil spill accidents (such as offshore drilling platform) may have distinguishing features and some important influencing factors may be ignored in the specific scenarios. Although this model may have some deficiencies in the specific scenarios, it does provide a practical solution and it should be useful in the decision support system to assist the decision-maker to make quick and reasonable response to oil spill from ships.

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