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An *n*-valued neutrosophic set method for the assessment of an offshore oil spill risk

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ABSTRACT

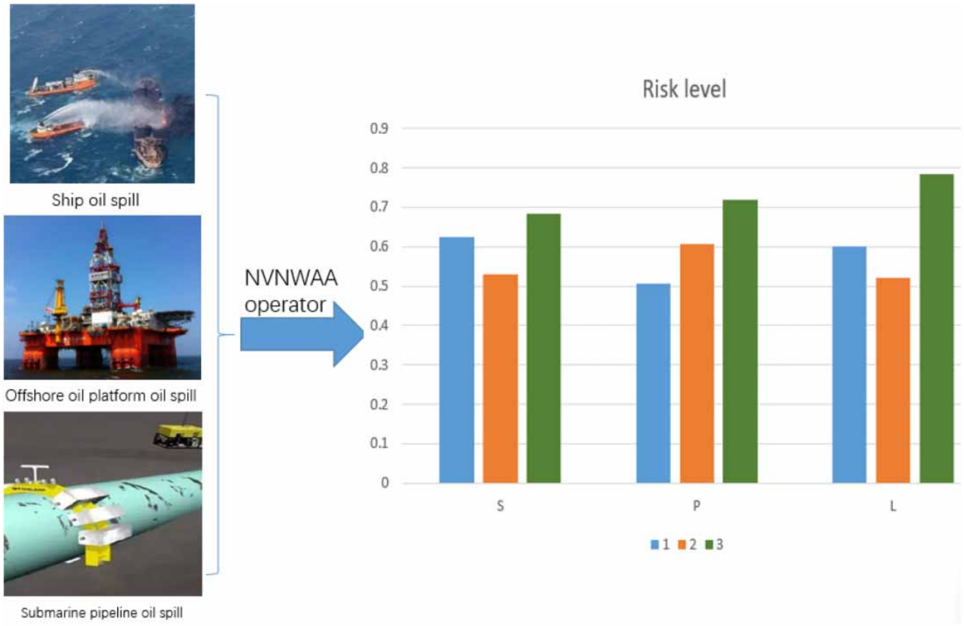
With the development of maritime transportation, oil spill accidents occur frequently. In this paper, a scientific and reasonable assessment of ship oil spills, offshore oil platform oil spills, and subsea pipeline oil spills is carried out, and a risk assessment method of an offshore oil spill based on an *n*-value neutrosophic set is proposed. First, the oil spill risk evaluation index systems of these three risk sources are constructed, respectively, and the entropy weight method is used to calculate the weight. Second, we establish a risk assessment model under the *n*-value neutrosophic environment. Furthermore, we use the *n*-value neutrosophic-weighted arithmetic average (NVNWAA) to calculate the risk levels of the following three risk sources: ship oil spills, offshore oil platform spills, and submarine pipeline spills. Finally, according to the results of the risk assessment, the countermeasures to strengthen the preventive measures of oil spill accidents are put forward.

Key words: *n*-value neutrosophic set, *n*-value neutrosophic-weighted arithmetic average operator (NVNWAA), oil spill

HIGHLIGHTS

- Establish risk assessment index systems for oil spills on ships, offshore oil platforms, and undersea pipelines.
- Propose an *n*-value neutrosophic-weighted arithmetic average operator.
- Propose the entropy weight method to calculate the weight of indexes.
- Develop an oil spill risk assessment model based on an *n*-value neutrosophic.
- Discuss the prevention measures related to an oil spill of three risk sources.

GRAPHICAL ABSTRACT



1. INTRODUCTION

With the rapid expansion of the coastal oil reserve base, the wharf's oil throughput and wharf's ship numbers increase sharply, then the risk of oil spills rose and oil spill accidents occurred occasionally, which bring enormous pressure to large influence on human health, safety, and economy, tourism and trade of coastline *et al.* The hazards of oil spills are as follows: (1) when crude oil or oil products are leaked at sea, due to the different oil composition, an oil film of varying thickness will be formed on the sea surface, which will reduce the photosynthesis of phytoplankton and affect the oxygen content of seawater. (2) The oil spill will stick to the feathers of seabirds and make them lose their ability to keep warm and fly. Seabirds that cannot fly will eventually die due to drowning, hunger, or loss of body temperature. (3) Harmful substances contained in the oil spill will accumulate in fish, shrimp, shells, and other organisms, and continue to pass through the food chain. If people eat contaminated seafood, these harmful substances will harm human health. In addition, the oil spill will also cause different degrees of impact on fishing, tourism, and so on.

The consequences of oil spill accidents are very serious, and oil spill risk assessment has become a hot research in the field of marine environmental protection. Domestic and foreign scholars have adopted different methods to analyze their respective research subjects. Common risk analysis methods include the neural network method, grey system method, Bayesian network method, accident tree method, analytic hierarchy process, risk matrix method, multilevel fuzzy comprehensive evaluation method, dynamic Bayesian model and machine learning, and so on. Xiao *et al.* proposed a method for the identification of oil spill risk degree in ship areas (Xiao *et al.* 2002). Yan & Ma proposed a grey fuzzy comprehensive evaluation (Yan & Ma 2011). Al-Amin *et al.* developed a new risk model to evaluate the possibility of ship collision, sinking, grounding, and other accidents (Baksh *et al.* 2018). Ozkan did some analysis by using fault tree analysis (Özkan 2016). Wu improved the traditional artificial neural network and used the double-layer particle swarm algorithm to evaluate the ship risk and reduce the error (Wu 2016). Maisa *et al.* analyzed the ecological impact of oil spills by a probabilistic framework (Nevalainen *et al.* 2016). Moonjin *et al.* built a risk matrix to assess the worst-case scenario for oil and toxic and hazardous substances in Korea's future (Lee & Jung 2013). Singh *et al.* developed an oil potential risk model and used a space model to identify the key areas of potential oil spill risk (Singh *et al.* 2015). Sun and Han established the evaluation module about the marine single-ship oil spill at Yangshan port according to the risk value and divided the risk level into four grades, and then used Visual Basic computer programming language to develop corresponding software tools for quantifying the monitoring and evaluation of ships in Shanghai Yangshan Port (Sun & Han 2010). Jin *et al.* analyzed the tanker accident probability by using some machine learning methods (Jin *et al.* 2019). Liu *et al.* used the analytical hierarchy process to make a method for ship oil spill risk (Liu *et al.* 2017). Zhang *et al.* used the fuzzy evaluation in the assessment model about marine oil spill pollution (Zhang *et al.* 2016). Pan used the fuzzy evaluation in the risk assessment of the oil tanker spill (Pan 2020).

We have too much dependence on the objective phenomenon, objective data, and objective indicators in oil spill risk assessment methods. However, in the actual oil spill risk assessment, we need to consider various factors, especially some uncertain factors, such as crew responsibilities, crew business skills and experience, crew health, and maintenance status. Therefore, this paper introduced neutrosophic sets (NSs) (Zadeh 1965; Smarandache 1998), because NS not only has true and false components but also has indeterminable components. To introduce NS theory into engineering applications, a single-valued neutrosophic set (SVNS) was proposed (Wang *et al.* 2010). When the index has multiple levels, we should need NVNS (Smarandache 2013) to settle these problems. NVNS consists of three independent subjection functions and can quantify the qualitative evaluation, solve the problems of ambiguity, difficulty in quantification and uncertainty, and can improve the prediction accuracy. Now NVNS plays an important tool in many domains (Ye & Ye 2014; Said *et al.* 2015; Fan & Ye 2017; Smarandache 2017; Fan *et al.* 2018, 2019; Fan 2019). The evaluation indexes of offshore oil spill risk sources generally have multiple levels, so we can use NVNS to establish the risk assessment model and use the NVNWAA operator to objectively evaluate and analyze to provide some advice for offshore oil spill risk evaluation. The new method proposed in this paper can represent uncertainty evaluation, and consider the subjective expression of some important people and key experts in shipping, to achieve better control of risk assessment.

Other parts are as follows: Section 2 constructs an index system of risk assessment about the three risk sources. Section 3 describes some concepts. Section 4 defines the NVNWAA operator. Section 5 establishes offshore oil spill risk assessment methods. Section 6 presents an example of this method and gives some suggestions. Section 7 concludes this paper.

2. THE INDEX SYSTEM OF RISK ASSESSMENT

Risk identification in oil spill is to comprehensively consider the possible factors, and then select valuable influencing factors to establish an index system of risk assessment. The main risk sources of offshore oil spill include ship oil spill, offshore oil platforms, submarine pipelines, oil processing enterprises, and offshore oil transportation. We choose the first three risk sources for oil spill risk assessment.

2.1. Ship oil spill

Combining the port channel conditions, and the natural environment, the risk factors of ship oil spills are analyzed to obtain the main factors that may affect ship oil spill risk. Then, through consulting experts, captains, and other important ship personnel to adjust and modify the evaluation indicators, the factors that ultimately affect the risk of oil spill are human, ship, ship management, and environment. Table 1 lists some indexes.

2.2. Offshore oil platform oil spill

The evaluation index system of oil spills on an offshore oil platform is shown in Table 2.

2.3. Submarine pipeline

The evaluation index system of the submarine pipeline oil spill is shown in Table 3.

2.4. Risk grade

According to the common classification principle of oil spill risk assessment, five risk grades can be classified: minimal, minor, general, great, and extremely great, which are, respectively, represented by ranges between 0 and 1, and Table 4 lists the corresponding relationship.

3. BASIC CONCEPTS OF SVNSS AND NVNSS

Definition 1 (Smarandache 1998)**.** NS is denoted by an object set Y with element y:

$$N = \{y, J_N(y), K_N(y), L_N(y) | y \in Y\},$$

where $J_N(y)$, $K_N(y)$, $L_N(y)$ express the truth, the indeterminacy, and the falsity membership function in the nonstandard interval $]^-0, 1^+[$, such that $J_N(y)$: $Y \rightarrow\ ]^-0, 1^+[$, $K_N(y)$: $Y \rightarrow\ ]^-0, 1^+[$, and $L_N(y)$:$Y \rightarrow\ ]^-0, 1^+[$. Then, the sum of $J_N(y)$, $K_N(y)$ and $L_N(y)$ satisfies $^-0 \leq J_N(y) + K_N(y) + L_N(y) \leq 3^+$.

Table 1 | The index system of risk assessment about ship oil spill

First-grade	Second-grade	Third-grade
Human factors	Responsibility of crew Business skills and experience of crew Physical condition of crew	
Ship factors	Age of vessel Tonnage Maintenance status Technical state of ship	
Environmental factors	The natural environment	Wind rating Wave height The velocity The visibility
	The port environment	Channel condition Navigation AIDS Navigable density
Management factors	Staffing and training Shipping company safety management system Management supervision and inspection	

Table 2 | The index system of risk assessment about offshore oil platform oil spill

First-grade	Second-grade
Oil overflow	
Oil characteristics	Toxicity Persistence Flammability Viscosity
Oil spill location	Sea-sensitive resources Offshore distance Coastal area category
Meteorological elements	Wind speed Visibility
Hydrological elements	Surface velocity Surface flow direction Surface water temperature Wave height

Definition 2 (Wang *et al.* 2010). SVNS is denoted by an object set Y with element y:

$$N = \{y, J_N(y), K_N(y), L_N(y) | y \in Y\},$$

where $J_N(y), K_N(y), L_N(y)$ express the truth, the indeterminacy, and the falsity of membership function, $J_N(y), K_N(y), L_N(y) \in [0, 1]$ and $0 \leq J_N(y) + K_N(y) + L_N(y) \leq 3$.

Definition 3 (Smarandache 2013). NVNS is denoted by an object set Y with element y:

$$N = \left\{ \left\langle \begin{matrix} y, (J_{1N}(y), J_{2N}(y), \ldots, J_{mN}(y)), (K_{1N}(y), K_{2N}(y), \ldots, \\ K_{mN}(y)), (L_{1N}(y), L_{2N}(y), \ldots, L_{mN}(y)) \end{matrix} \right\rangle | y \in Y \right\},$$

Table 3 | The index system of risk assessment about submarine pipeline oil spill

First-grade	Second-grade	Third-grade
Pipeline corrosion	External corrosion	Environmental corrosion Cathodic protection Pipeline property Stress corrosion Number of years
	Internal corrosion	Fluid properties Internal corrosion protection
	Age and corrosion detection	
Fatigue aging	Pressure safety factor Pipe diameter Pipeline life Wave current scour Mitigation measures	
Nature break forces	Soil movement Extreme weather	
Third-party damage	Overburden condition Water activity level Preventive measures against damage Identification of the sea area around the pipeline	
misoperation	Safety check Technological procedure Safety record Training situation	
	Comprehensive quality of personnel	Business capability Sense of responsibility

Table 4 | Risk grade

Risk grade	Score value range
Extremely great	[0, 0.2]
Great	[0.2, 0.4]
General	[0.4, 0.6]
Minor	[0.6, 0.8]
Minimal	[0.8, 1]

where $J_{1N}(y), J_{2N}(y), \ldots, J_{mN}(y), K_{1N}(y), K_{2N}(y), \ldots, K_{mN}(y), L_{1N}(y), L_{2N}(y), \ldots, L_{mN}(y) \in [0, 1]$, and $0 \le J_{iN}(y) + K_{iN}(y) + L_{iN}(y) \le 3 (i = 1, 2, \ldots, m)$, m is a positive integer.

Definition 4 (Smarandache 2013; Ye *et al.* 2015)**.** Two NVNSs Z and F are denoted by object set Y with element y

$$Z = \left\{ \left\langle \begin{array}{c} y, (J_{1Z}(y), J_{2Z}(y), \ldots, J_{mZ}(y)), (K_{1Z}(y), K_{2Z}(y), \ldots, \\ K_{mZ}(y)), (L_{1Z}(y), L_{2Z}(y), \ldots, L_{mZ}(y)) \end{array} \right\rangle | y \in Y \right\},$$

$$F = \left\{ \left\langle \begin{array}{c} y, (J_{1F}(y), J_{2F}(y), \ldots, J_{mF}(y)), (K_{1F}(y), K_{2F}(y), \ldots, \\ K_{mF}(y)), (L_{1F}(y), L_{2F}(y), \ldots, L_{mF}(y)) \end{array} \right\rangle | y \in Y \right\}.$$

The relations between Z and F are listed:

I $Z = F$, just $J_{iZ}(y) = J_{iF}(y)$, $K_{iZ}(y) = K_{iF}(y)$, $L_{iZ}(y) = L_{iF}(y)$ for $i = 1, 2, \ldots, m$;

$$\text{Ⅱ}\ \ Z \cup F = \left\{ \left\langle \begin{array}{l} y, (J_{1Z}(y) \vee J_{1F}(y), J_{2Z}(y) \vee J_{2F}(y), \ \ldots, J_{mZ}(y) \vee J_{mF}(y)) \\ (K_{1Z}(y) \wedge K_{1F}(y), K_{2Z}(y) \wedge K_{2F}(y), \ \ldots, K_{mZ}(y) \wedge K_{mF}(y)), \\ (L_{1Z}(y) \wedge L_{1F}(y), L_{2Z}(y) \wedge L_{2F}(y), \ \ldots, L_{mZ}(y) \wedge L_{mF}(y)) \end{array} \right\rangle | y \in Y \right\};$$

$$\text{Ⅲ}\ \ Z \cap F = \left\{ \left\langle \begin{array}{l} y, (J_{1Z}(y) \wedge J_{1F}(y), J_{2Z}(y) \wedge J_{2F}(y), \ \ldots, J_{mZ}(y) \wedge J_{mF}(y)) \\ (K_{1Z}(y) \vee K_{1F}(y), K_{2Z}(y) \vee K_{2F}(y), \ \ldots, K_{mZ}(y) \vee K_{mF}(y)), \\ (L_{1Z}(y) \vee L_{1F}(y), L_{2Z}(y) \vee L_{2F}(y), \ \ldots, L_{mZ}(y) \vee L_{mF}(y)) \end{array} \right\rangle | y \in Y \right\}.$$

For convenience, NVNN is denoted by $z = \langle J_{1z}, J_{2z}, \ \ldots, J_{mz}, K_{1z}, K_{2z}, \ \ldots, K_{mz}, L_{1z}, L_{2z}, \ \ldots, L_{mz} \rangle$.

Definition 5 (Smarandache 2013; Ye *et al.* 2015)**.** Two NVNNs be $z = \langle J_{1z}, J_{2z}, \ \ldots, J_{mz}, K_{1z}, K_{2z}, \ \ldots, K_{mz}, L_{1z}, L_{2z}, \ \ldots, L_{mz} \rangle$ and $f = \langle J_{1f}, J_{2f}, \ \ldots, J_{mf}, K_{1f}, K_{2f}, \ \ldots, K_{mf}, L_{1f}, L_{2f}, \ \ldots, L_{mf} \rangle$. The operational rules of them are listed as follows:

$$z + f = \left\langle \begin{array}{l} (J_{1z} + J_{1f} - J_{1z}J_{1f}, J_{2z} + J_{2f} - J_{2z}J_{2f}, \ \ldots, J_{mz} + J_{mf} - J_{mz}J_{mf}), \\ (K_{1z}K_{1f}, K_{2z}K_{2f}, \ \ldots, K_{mz}K_{mf}), (L_{1z}L_{1f}, L_{2z}L_{2f}, \ \ldots, L_{mz}L_{mf}) \end{array} \right\rangle; \tag{1}$$

$$z \times f = \left\langle \begin{array}{l} (J_{1z}J_{1f}, J_{2z}J_{2f}, \ \ldots, J_{mz}J_{mf}), \\ (K_{1z} + K_{1f} - K_{1z}K_{1f}, K_{2z} + K_{2f} - K_{2z}K_{2f}, \ \ldots, K_{mz} + K_{mf} - K_{mz}K_{mf}), \\ (L_{1z} + L_{1f} - L_{1z}L_{1f}, L_{2z} + L_{2f} - L_{2z}L_{2f}, \ \ldots, L_{mz} + L_{mf} - L_{mz}L_{mf}) \end{array} \right\rangle; \tag{2}$$

$$\varphi z = \left\langle \begin{array}{l} (1 - (1 - J_{1z})^{\varphi}, 1 - (1 - J_{2z})^{\varphi}, \ \ldots, 1 - (1 - J_{mz})^{\varphi}), \\ ((K_{1z})^{\varphi}, (K_{2z})^{\varphi}, \ \ldots, (K_{mz})^{\varphi}), ((L_{1z})^{\varphi}, (L_{2z})^{\varphi}, \ \ldots, (L_{mz})^{\varphi}) \end{array} \right\rangle; \tag{3}$$

$$z^{\varphi} = \left\langle \begin{array}{l} ((J_{1z})^{\varphi}, (J_{2z})^{\varphi}, \ \ldots, (J_{mz})^{\varphi}), \\ (1 - (1 - K_{1z})^{\varphi}, 1 - (1 - K_{2z})^{\varphi}, \ \ldots, 1 - (1 - K_{mz})^{\varphi}), \\ (1 - (1 - L_{1z})^{\varphi}, 1 - (1 - L_{2z})^{\varphi}, \ \ldots, 1 - (1 - L_{mz})^{\varphi}) \end{array} \right\rangle. \tag{4}$$

Definition 6 (Chen & Ye 2017)**.** The single-valued neutrosophic weighted arithmetic average (SVNWAA) operator of $z_j = \langle J_j, K_j, L_j \rangle (j = 1, 2, \ \ldots, m)$ is introduced as follows:

$$SVNWAA(z_1, z_2, \ \ldots, z_m) = \sum_{j=1}^{m} u_j z_j = \left\langle 1 - \prod_{j=1}^{m} (1 - J_j)^{u_j}, \ \prod_{j=1}^{m} (K_j)^{u_j}, \ \prod_{j=1}^{m} (L_j)^{u_j} \right\rangle, \tag{5}$$

where u_j is the weight of z_j for $u_j \in [0, 1]$ and $\sum\limits_{j=1}^{m} u_j = 1$.

Definition 7 (Chen & Ye 2017)**.** Set $z = \langle J, K, L \rangle$ as SVNN, the score and accurate values can be defined as follows:

$$Q(m) = (2 + J - K - L)/3, Q(m) \in [0, 1], \tag{6}$$

$$Y(m) = (J - K), Y(m) \in [-1, 1]. \tag{7}$$

4. NVNWAA OPERATOR

Definition 8. The *n*-value neutrosophic weighted arithmetic average (NVNWAA) operator of $z_j = \left\langle (J_{1z_j}, J_{2z_j}, \ \ldots, J_{n_j z_j}), (K_{1z_j}, K_{2z_j}, \ \ldots, K_{n_j z_j}), (L_{1z_j}, L_{2z_j}, \ \ldots, L_{n_j z_j}) \right\rangle$ $(j = 1, 2, \ldots, m)$ is introduced as follows:

$$NVNWAA(z_1, z_2, \ \ldots, z_m) = \sum_{j=1}^{m} u_j \sum_{i=1}^{n_j} \omega_{ji} z_j, \tag{8}$$

where u_j is the weight of z_j, $\sum_{j=1}^{m} u_j = 1$ and $u_j \in [0, 1]$, ω_{ji} is the weight of the sub-elements $J_{iz_j}(y), K_{iz_j}(y), L_{iz_j}(y)$ $(i = 1, 2, \ \ldots, n_j)$ in z_j with $\omega_{ji} \in [0, 1]$ and $\sum_{i=1}^{n_j} \omega_{ji} = 1$.

Theorem 1. Set NVNNs $z_j = \left\langle (J_{1z_j}, J_{2z_j}, \ldots, J_{n_j z_j}), (K_{1z_j}, K_{2z_j}, \ldots, K_{n_j z_j}), (L_{1z_j}, L_{2z_j}, \ldots, L_{n_j z_j}) \right\rangle$ ($j = 1, 2, \ldots, m$), the following formula can be got according to Definitions 5 and 6:

$$NVNWAA(z_1, z_2, \ldots, z_m) = \sum_{j=1}^{m} u_j \sum_{i=1}^{n_j} \omega_{ji} z_j = \left\langle 1 - \prod_{j=1}^{m}\prod_{i=1}^{n_j}(1 - J_{iz_j})^{u_j \omega_{ji}}, \prod_{j=1}^{m}\prod_{i=1}^{n_j}(K_{iz_j})^{u_j \omega_{ji}}, \prod_{j=1}^{m}\prod_{i=1}^{n_j}(L_{iz_j})^{u_j \omega_{ji}} \right\rangle, \tag{9}$$

where u_j is the weight of z_j, $\sum_{j=1}^{m} u_j = 1$ and $u_j \in [0, 1]$, ω_{ji} is the weight of the sub-elements $J_{iz_j}(y), K_{iz_j}(y), L_{iz_j}(y) (i = 1, 2, \ldots, n_j)$ in z_j with $\omega_{ji} \in [0, 1]$ and $\sum_{i=1}^{n_j} \omega_{ji} = 1$.

Proof:

(a) $$\omega_{ji} z_j = \omega_{ji} \left\langle \begin{matrix} (J_{1z_j}, J_{2z_j}, \ldots, J_{n_j z_j}), \\ (K_{1z_j}, K_{2z_j}, \ldots, K_{n_j z_j}), \\ (L_{1z_j}, L_{2z_j}, \ldots, L_{n_j z_j}) \end{matrix} \right\rangle = \begin{pmatrix} (1-(1-J_{1z_j})^{\omega_{j1}}, 1-(1-J_{2z_j})^{\omega_{j2}}, \cdots, 1-(1-J_{n_j z_j})^{\omega_{ji}}), \\ ((K_{1z_j})^{\omega_{j1}}, (K_{2z_j})^{\omega_{j2}}, \cdots, (K_{n_j z_j})^{\omega_{ji}}), \\ ((L_{1z_j})^{\omega_{j1}}, (L_{2z_j})^{\omega_{j2}}, \cdots, (L_{n_j z_j})^{\omega_{ji}}) \end{pmatrix};$$

(b) $$\sum_{i=1}^{n_i} \omega_{ji} z_j = \left\langle 1 - \prod_{i=1}^{n_j} (1 - J_{iz_j})^{\omega_{ji}}, \prod_{i=1}^{n_j} (K_{iz_j})^{\omega_{ji}}, \prod_{i=1}^{n_j} (L_{iz_j})^{\omega_{ji}} \right\rangle;$$

(c) $$u_j \sum_{i=1}^{n_j} \omega_{ji} z_j = u_j \left\langle 1 - \prod_{i=1}^{n_j} (1 - J_{iz_j})^{\omega_{ji}}, \prod_{i=1}^{n_j} (K_{iz_j})^{\omega_{ji}}, \prod_{i=1}^{n_j} (L_{iz_j})^{\omega_{ji}} \right\rangle$$
$$= \left\langle 1 - \prod_{i=1}^{n_j} (1 - J_{iz_j})^{\omega_{ji} u_j}, \prod_{i=1}^{n_j} (K_{iz_j})^{\omega_{ji} u_j}, \prod_{i=1}^{n_j} (L_{iz_j})^{\omega_{ji} u_j} \right\rangle;$$

(d) $$\sum_{j=1}^{m} u_j \sum_{i=1}^{n_j} \omega_{ji} z_j = \left\langle 1 - \prod_{j=1}^{m}\prod_{i=1}^{n_j} (1 - J_{iz_j})^{u_j \omega_{ji}}, \prod_{j=1}^{m}\prod_{i=1}^{n_j} (K_{iz_j})^{u_j \omega_{ji}}, \prod_{j=1}^{m}\prod_{i=1}^{n_j} (L_{iz_j})^{u_j \omega_{ji}} \right\rangle.$$

Equation (9) is true based on (a)–(d).

5. ASSESSMENT METHOD USING ENTROPY WEIGHTS AND THE NVNWAA OPERATOR

5.1. Entropy weight method

Using the entropy weight method, each index's weight can be got by the following four steps.

Step 1: For m samples and n indexes, then s_{ab} is the value of the index b of sample a, if each index's normalized value is $\Phi_1, \Phi_2, \ldots, \Phi_n$, then for the positive index, the normalization formula is $\phi_{ab} = s_{ab} - min(S_a)/\max(S_a) - min(S_a)$.

While the indicators are negative, the normalization formula is $\phi_{ab} = \max(S_a) - s_{ab}/\max(S_a) - \min(S_a)$.

Step 2: The information entropy $E_b = -1/\ln m \sum_{a=1}^{m} p_{ab} \ln p_{ab}$, $b = 1, \ldots, n$, in which $p_{ab} = \phi_{ab}/\sum_{a=1}^{m} \phi_{ab}$.

Step 3: According to the calculation formula of information entropy, the information entropy of each index is calculated as $E_1, E_2, \ldots, E_n$. Each index's weight can be calculated by $u_b = 1 - E_b/n - \sum_{b=1}^{n}(E_b)$.

Step 4: Calculate the composite index $\phi'_{a\tilde{b}} = \sum_{b=1}^{n} u_b(\phi_{ab})$, in which $\phi'_{a\tilde{b}}$ express the previous level number, $\tilde{b}$ express the number of indexes of the previous level. By repeating steps 1 ~ 4, we can calculate the weight of each index.

5.2. Assessment methods using the NVNWAA operator

Some indexes are multilevel in risk assessment of offshore oil spills, thus, we can use NVNS to represent them. Assuming that an index set is $Z = \{z_1, z_2, \ldots, z_m\}$, $z_a (a = 1, 2, \ldots, m)$ contains n_a sub-indexes, denoted by a sub-index set $z_a = \{z_{a1}, z_{a2}, \ldots, z_{an_a}\}$. Then, each index z_a can be expressed by the NVNN $z_a = \left\langle (J_{1z_a}, J_{2z_a}, \ldots, J_{n_a z_a}), (K_{1z_a}, K_{2z_a}, \ldots, K_{n_a z_a}), (L_{1z_a}, L_{2z_a}, \ldots, L_{n_a z_a}) \right\rangle (a = 1, 2, \ldots, m)$. Table 5 shows the NVNN assessment matrix.

Table 5 | Assessment matrix

	$z_{a1}, z_{a2}, \ldots, z_{an_a}$
z_1	$\langle (J_{11}, J_{21}, \ldots, J_{n_1 1}), (K_{11}, K_{21}, \ldots, K_{n_1 1}), (L_{11}, L_{21}, \ldots, L_{n_1 1}) \rangle$
z_2	$\langle (J_{12}, J_{22}, \ldots, J_{n_2 2}), (K_{12}, K_{22}, \ldots, K_{n_2 2}), (L_{12}, L_{22}, \ldots, L_{n_2 2}) \rangle$
…	…
z_m	$\langle (J_{1n}, J_{2n}, \ldots, J_{n_m m}), (K_{1m}, K_{2m}, \ldots, K_{n_m m}), (L_{1m}, L_{2m}, \ldots, L_{n_m m}) \rangle$

According to the assessment matrix of Table 3, we establish a risk assessment method, it has four steps:

Step 1: According to the information entropy, the sub-indexes' weight vector $\omega_a = (\omega_{a1,}\omega_{a2,} \ldots, \omega_{ab})^T (a = 1, 2, \ldots, m; b = 1, 2, \ldots, n_a)$ and the indexes' weight vector $u = (u_{1,}u_{2,} \ldots, u_a)^T (a = 1, 2, \ldots, m)$ can be calculated.

Step 2: Using NVNWAA operator with ω_a and u, we get the collective SVNN:

$$NVNWAA(z_1, z_2, \ldots, z_m) = \sum_{a=1}^{m} u_a \sum_{b=1}^{n_a} \omega_{ab} z_a = \left\langle 1 - \prod_{a=1}^{m} \prod_{b=1}^{n_a} (1 - J_{bz_a})^{u_a \omega_{ab}}, \prod_{a=1}^{m} \prod_{b=1}^{n_a} (K_{bz_a})^{u_a \omega_{ab}}, \prod_{a=1}^{m} \prod_{b=1}^{n_a} (L_{bz_a})^{u_a \omega_{ab}} \right\rangle, \tag{10}$$

Step 3: The score values can be calculated by Equation (6).

Step 4: According to Table 4, risk levels can be determined.

Flow chart of the algorithm is shown in Figure 1.

6. APPLICATION OF THE PROPOSED ASSESSMENT METHOD

6.1. Evaluation data of ship oil spill

In this part, we simulated the basic data of three ships according to the risk assessment indexes to verify the feasibility of new methods. In the future, these methods can be tested in a more realistic environment. Here ship 1 to ship 3 are used to represent three different ships. Risk assessment index data of the three ship areas are shown in Table 6 under *n*-value neutrosophic information.

Table 7 lists the decision matrix.

In Table 7, we can see that every number is smaller than 1, so when we calculate the weight, we can skip Step 1 in Section 5.1, with Steps 2–4 in Section 5.1 we calculate the information entropy E, the results are shown in Table 8 (we only put T value to calculate).

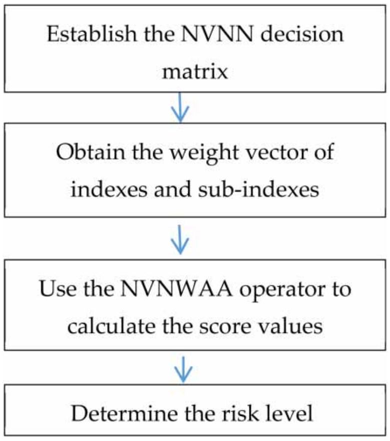


Figure 1 | Flow chart of the algorithm.

Table 6 | NVNN evaluation data of ship

	Ship 1	Ship 2	Ship 3
Responsibility of crew	0.1,0.2,0.9	0.5,0.8,0.3	0.9,0.1,0.1
Business skills and experience of crew	0.5,0.6,0.5	0.2,0.8,0.9	0.7,0.6,0.3
Physical condition of crew	0.7,0.2,0.3	0.5,0.9,0.6	0.4,0.3,0.7
Age of vessel	0.2,0.4,0.9	0.5,0.8,0.5	0.8,0.9,0.3
Tonnage	0.2,0.8,0.9	0.6,0.4,0.6	0.7,0.8,0.3
Maintenance status	0.1,0.2,0.9	0.6,0.5,0.5	0.8,0.6,0.3
Technical state of ship	0.5,0.6,0.5	0.5,0.8,0.5	0.7,0.6,0.4
Wind rating	0.9,0.1,0.1	0.7,0.3,0.3	0.9,0.1,0.1
Wave height	0.9,0.2,0.1	0.7,0.3,0.3	0.9,0.1,0.1
Velocity	0.9,0.1,0.2	0.8,0.2,0.4	0.9,0.2.0.1
Visibility	0.8,0.5,0.3	0.7,0.3,0.3	0.8,0.2,0.4
Channel condition	0.7,0.3,0.3	0.8,0.4,0.3	0.9,0.6,0.1
Navigation AIDS	0.8,0.3,0.3	0.7,0.6,0.3	0.9,0.2,0.1
Navigable density	0.8,0.3,0.4	0.8,0.5,0.3	0.7,0.2,0.4
Staffing and training	0.9,0.1,0.2	0.6,0.2,0.5	0.3,0.2.0.8
Shipping company safety management system	0.8,0.3,0.3	0.7,0.6,0.3	0.8,0.2,0.3
Management supervision and inspection	0.9,0.1,0.2	0.5,0.2,0.6	0.2,0.2.0.9

With the weight vector and Equation (10), then the collective SVNN of z_3 can be obtained, which are listed as follows:

$$z_3^1 = \langle 0.8890, 0.1464, 0.1643 \rangle$$

$$z_3^2 = \langle 0.8272, 0.2905, 0.2442 \rangle$$

$$z_3^3 = \langle 0.9323, 0.1637, 0.0715 \rangle$$

z_3^1 expresses z_3 of S_1, z_3^2 expresses z_3 of S_2 and z_3^3 expresses z_3 of S_3. The weight vector of the sub-indexes of z_3 is 1.

Table 7 | NVNN matrix of ship

		S_1	S_2	S_3
$\mathrm{z}_1 = \{\mathrm{z}_{11}, z_{12}, z_{13}\}$		$\left\langle \begin{array}{c} (0.1, 0.5, 0.7), \\ (0.2, 0.6, 0.2), \\ (0.9, 0.5, 0.3) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.5, 0.2, 0.5), \\ (0.8, 0.8, 0.9), \\ (0.3, 0.9, 0.6) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.9, 0.7, 0.4), \\ (0.1, 0.6, 0.3), \\ (0.1, 0.3, 0.7) \end{array} \right\rangle$
$z_2 = \{z_{21}, z_{22}, z_{23}, z_{24}\}$		$\left\langle \begin{array}{c} (0.2, 0.2, 0.1, 0.5), \\ (0.4, 0.8, 0.2, 0.6), \\ (0.9, 0.9, 0.9, 0.5) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.5, 0.6, 0.6, 0.5), \\ (0.8, 0.4, 0.5, 0.8), \\ (0.5, 0.6, 0.5, 0.5) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.8, 0.7, 0.8, 0.7), \\ (0.9, 0.8, 0.6, 0.6), \\ (0.3, 0.3, 0.3, 0.4) \end{array} \right\rangle$
$z_3(z_{31}, z_{32})$	$z_{31}(z_{311}, z_{312}, z_{313}, z_{314})$	$\left\langle \begin{array}{c} (0.9, 0.9, 0.9, 0.8), \\ (0.1, 0.2, 0.1, 0.5), \\ (0.1, 0.1, 0.2, 0.3) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.7, 0.7, 0.8, 0.7), \\ (0.3, 0.3, 0.2, 0.3), \\ (0.3, 0.3, 0.4, 0.3) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.9, 0.9, 0.9, 0.8), \\ (0.1, 0.1, 0.2, 0.2), \\ (0.1, 0.1, 0.1, 0.4) \end{array} \right\rangle$
	$z_{32}(z_{321}, z_{322}, z_{323})$	$\left\langle \begin{array}{c} (0.7, 0.8, 0.8), \\ (0.3, 0.3, 0.3), \\ (0.3, 0.3, 0.4) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.8, 0.7, 0.8), \\ (0.4, 0.6, 0.5), \\ (0.3, 0.3, 0.3) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.9, 0.9, 0.7), \\ (0.6, 0.2, 0.2), \\ (0.1, 0.1, 0.4) \end{array} \right\rangle$
$z_4(z_{41}, z_{42}, z_{43})$		$\left\langle \begin{array}{c} (0.9, 0.8, 0.9), \\ (0.1, 0.3, 0.1), \\ (0.2, 0.3, 0.2) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.6, 0.7, 0.5), \\ (0.2, 0.6, 0.2), \\ (0.5, 0.3, 0.6) \end{array} \right\rangle$	$\left\langle \begin{array}{c} (0.3, 0.8, 0.2), \\ (0.2, 0.2, 0.2), \\ (0.8, 0.3, 0.9) \end{array} \right\rangle$

Table 8 | *E*-value of ship

First-grade	Weight	Second-grade	Weight	Third-grade	Weight
Human factors	0.2844	Responsibility of crew	0.6481		
		Business skills and experience of crew	0.2809		
		Physical condition of crew	0.0710		
Ship factors	0.3895	Age of vessel	0.2758		
		Tonnage	0.2313		
		Maintenance status	0.4642		
		Technical state of ship	0.0287		
Environmental factors	0.0095	The natural environment	0.2861	Wind rating	0.3970
				Wave height	0.3970
				The velocity	0.0903
				The visibility	0.1157
		The port environment	0.7139	Channel condition	0.4224
				Navigation AIDS	0.4224
				Navigable density	0.1552
Management factors	0.3165	Staffing and training	0.3623		
		Shipping company safety management system	0.0080		
		Management supervision and inspection	0.6297		

With the weight vector and Equation (10), then the collective SVNN of the alternative $S_r(r = 1, 2, 3)$ can be obtained, which are listed as follows:

$$S_1 = \langle 0.6006, 0.2167, 0.5106\rangle$$

$$S_2 = \langle 0.5307, 0.4401, 0.5006\rangle$$

$$S_3 = \langle 0.7082, 0.3180, 0.3436\rangle$$

According to Equation (6), we get $Q(S_r)$ as follows:

$$Q(S_1) = 0.6245$$

$$Q(S_2) = 0.5300$$

$$Q(S_3) = 0.6822$$

By comparing with Table 4, we can conclude that ships 1 and 3 are at minor risk, and ship 3 is in the best condition. According to the historical data, the model results are the same as the real results. It is effective to verify the risk assessment with *n*-value neutrosophic comprehensive evaluation method, which can get an obvious effect and high credibility. The evaluation results can be applied to ship oil spill-related aspects.

6.2. Evaluation data of offshore oil platform oil spill

Here P1 to P3 are used to represent three different oil platforms. Risk assessment index data of the three platforms are shown in Table 9 under *n*-value neutrosophic information.

Table 10 lists the decision matrix.

In Table 10, we can see that every number is smaller than 1, so when we calculate the weight, we can skip Step 1 in Section 5.1, with Steps 2–4 in Section 5.1 we calculate the information entropy *E*, the results are shown in Table 11 (we only put *T* value to calculate).

Table 9 | NVNN evaluation data of offshore oil platform

	P1	P2	P3
Oil overflow	0.8,0.5,0.3	0.7,0.3,0.3	0.8,0.2,0.4
Toxicity	0.5,0.6,0.5	0.2,0.8,0.9	0.7,0.6,0.3
Persistence	0.8,0.9,0.3	0.2,0.4,0.9	0.5,0.8,0.5
Flammability	0.6,0.5,0.5	0.1,0.2,0.9	0.8,0.6,0.3
Viscosity	0.2,0.8,0.9	0.6,0.4,0.6	0.7,0.8,0.3
Sea sensitive resources	0.8,0.9,0.3	0.7,0.3,0.3	0.9,0.1,0.1
Offshore distance	0.9,0.2,0.1	0.8,0.2,0.4	0.7,0.6,0.4
Coastal area category	0.1,0.2,0.9	0.5,0.8,0.3	0.7,0.2,0.3
Wind speed	0.5,0.9,0.6	0.7,0.3,0.3	0.9,0.1,0.1
Visibility	0.5,0.8,0.5	0.5,0.8,0.3	0.9,0.2.0.1
Surface velocity	0.8,0.2,0.4	0.9,0.6,0.1	0.5,0.6,0.5
Surface flow direction	0.9,0.1,0.1	0.9,0.1,0.1	0.4,0.3,0.7
Surface water temperature	0.7,0.3,0.3	0.8,0.4,0.3	0.7,0.3,0.3
Wave height	0.9,0.1,0.2	0.5,0.2,0.6	0.2,0.2.0.9

Table 10 | NVNN matrix of offshore oil platform

	P_1	P_2	P_3
z_1	$\langle 0.8, 0.5, 0.3\rangle$	$\langle 0.7, 0.3, 0.3\rangle$	$\langle 0.8, 0.2, 0.4\rangle$
$z_2(z_{21}, z_{22}, z_{23}, z_{24})$	$\left\langle \begin{array}{c}(0.5, 0.8, 0.6, 0.2),\\(0.6, 0.9, 0.5, 0.8),\\(0.5, 0.3, 0.5, 0.9)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.2, 0.2, 0.1, 0.6),\\(0.8, 0.4, 0.2, 0.4),\\(0.9, 0.9, 0.9, 0.6)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.7, 0.5, 0.8, 0.7),\\(0.6, 0.8, 0.6, 0.8),\\(0.3, 0.5, 0.3, 0.3)\end{array}\right\rangle$
$z_3(z_{31}, z_{32}, z_{33})$	$\left\langle \begin{array}{c}(0.8, 0.9, 0.1),\\(0.9, 0.2, 0.2),\\(0.3, 0.1, 0.9)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.7, 0.8, 0.5),\\(0.3, 0.2, 0.8),\\(0.3, 0.4, 0.3)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.9, 0.7, 0.7),\\(0.1, 0.6, 0.2),\\(0.1, 0.4, 0.3)\end{array}\right\rangle$
$z_4(z_{41}, z_{42})$	$\left\langle \begin{array}{c}(0.5, 0.5),\\(0.9, 0.8),\\(0.6, 0.5)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.7, 0.5),\\(0.3, 0.8),\\(0.3, 0.3)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.9, 0.9),\\(0.1, 0.2),\\(0.1, 0.1)\end{array}\right\rangle$
$z_5(z_{51}, z_{52}, z_{53}, z_{54})$	$\left\langle \begin{array}{c}(0.8, 0.9, 0.7, 0.9),\\(0.2, 0.1, 0.3, 0.1),\\(0.4, 0.1, 0.3, 0.2)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.9, 0.9, 0.8, 0.5),\\(0.6, 0.1, 0.4, 0.2),\\(0.1, 0.1, 0.3, 0.6)\end{array}\right\rangle$	$\left\langle \begin{array}{c}(0.5, 0.4, 0.7, 0.2),\\(0.6, 0.3, 0.3, 0.2),\\(0.5, 0.7, 0.3, 0.9)\end{array}\right\rangle$

With the weight vector and Equation (10), then the collective SVNN of the alternative $P_r(r = 1, 2, 3)$ can be obtained, which are listed as follows:

$$P_1 = \langle 0.4514, 0.3180, 0.6120\rangle$$

$$P_2 = \langle 0.4914, 0.2697, 0.3994\rangle$$

$$P_3 = \langle 0.7255, 0.2769, 0.2913\rangle$$

According to Equation (6), we get $Q(P_r)$ as follows:

$$Q(P_1) = 0.5072$$

$$Q(P_2) = 0.6074$$

$$Q(P_3) = 0.7191$$

Table 11 | *E*-value of offshore oil platform

First-grade	Weight	Second-grade	Weight
Oil overflow	0.0065		
Oil characteristics	0.2737	Toxicity	0.1902
		Persistence	0.2299
		Flammability	0.3870
		Viscosity	0.1929
Oil spill location	0.5357	Sea sensitive resources	0.0248
		Offshore distance	0.0248
		Coastal area category	0.9504
Meteorological elements	0.1114	Wind speed	0.3963
		Visibility	0.6037
Hydrological elements	0.0728	Surface velocity	0.1186
		Surface flow direction	0.2396
		Surface water temperature	0.0085
		Wave height	0.6333

By comparing with Table 4, we can conclude that platforms 2 and 3 are at minor risk, and platform 3 is in the best condition.

6.3. Evaluation data of submarine pipeline oil spill

Here L1 to L3 are used to represent three different submarine pipelines. Risk assessment index data of the three submarine pipelines are shown in Table 12 under *n*-value neutrosophic information.

Table 13 lists the decision matrix.

In Table 13, we can see that every number is smaller than 1, so when we calculate the weight, we can skip Step 1 in Section 5.1, with Steps 2–4 in Section 5.1 we calculate the information entropy *E*, the results are shown in Table 14 (we only put *T* value to calculate).

With the weight vector and Equation (10), then the collective SVNN of z_1 and z_5 can be obtained, which are listed as follows:

$$z_1^1 = \langle 0.3941, 0.5338, 0.6649\rangle$$

$$z_1^2 = \langle 0.6803, 0.5527, 0.3884\rangle$$

$$z_1^3 = \langle 0.6972, 0.3140, 0.3245\rangle$$

z_1^1 expresses z_1 of L_1, z_1^2 expresses z_1 of L_2 and z_1^3 expresses z_1 of L_3. The weight vector of the sub-indexes of z_1 is 1.

$$z_5^1 = \langle 0.4207, 0.2516, 0.4781\rangle$$

$$z_5^2 = \langle 0.5051, 0.5918, 0.5785\rangle$$

$$z_5^3 = \langle 0.8484, 0.3145, 0.1563\rangle$$

z_5^1 expresses z_5 of L_1, z_5^2 expresses z_5 of L_2 and z_5^3 expresses z_5 of L_3. The weight vector of the sub-indexes of z_5 is 1.

Table 12 | NVNN evaluation data of submarine pipeline

	L1	L2	L3
Environmental corrosion	0.3,0.2.0.8	0.7,0.6,0.3	0.7,0.3,0.3
Cathodic protection	0.7,0.6,0.4	0.8,0.6,0.3	0.7,0.6,0.3
Pipeline property	0.2,0.8,0.9	0.8,0.4,0.3	0.9,0.2,0.1
Stress corrosion	0.6,0.4,0.5	0.7,0.2,0.5	0.9,0.9,0.2
Number of years	0.6,0.5,0.9	0.8,0.4,0.6	0.6,0.8,0.3
Fluid properties	0.7,0.2,0.4	0.5,0.5,0.5	0.6,0.6,0.3
Internal corrosion protection	0.5,0.1,0.6	0.8,0.2,0.4	0.7,0.2.0.4
Age and corrosion detection	0.5,0.6,0.5	0.5,0.8,0.5	0.2,0.4,0.9
Pressure safety factor	0.7,0.2,0.3	0.7,0.3,0.3	0.8,0.1,0.1
Pipe diameter	0.9,0.1,0.1	0.7,0.3,0.3	0.9,0.1,0.1
Pipeline life	0.4,0.2,0.1	0.7,0.3,0.3	0.7,0.1,0.1
Wave current scour	0.9,0.1,0.2	0.8,0.2,0.4	0.9,0.2.0.1
Mitigation measures	0.8,0.5,0.3	0.7,0.3,0.3	0.8,0.2,0.4
Soil movement	0.8,0.3,0.3	0.7,0.6,0.3	0.8,0.2,0.3
Extreme weather	0.8,0.3,0.3	0.5,0.6,0.5	0.6,0.2,0.3
Overburden condition	0.8,0.3,0.4	0.8,0.5,0.3	0.7,0.2,0.4
Water activity level	0.9,0.1,0.2	0.6,0.2,0.5	0.4,0.3,0.7
Preventive measures against damage	0.5,0.3,0.6	0.7,0.6,0.3	0.8,0.2,0.3
Identification of the sea area around the pipeline	0.3,0.2,0.9	0.5,0.8,0.3	0.9,0.1,0.1
Safety check	0.3,0.4,0.7	0.5,0.5,0.6	0.8,0.3,0.1
Technological procedure	0.5,0.2,0.3	0.5,0.9,0.6	0.9,0.3,0.2
Safety record	0.4,0.2,0.7	0.5,0.9,0.6	0.8,0.4,0.2
Training situation	0.5,0.2,0.3	0.5,0.4,0.5	0.9,0.3,0.2
Business capability	0.7,0.4,0.4	0.7,0.7,0.6	0.7,0.3,0.2
Sense of responsibility	0.4,0.1,0.2	0.6,0.2,0.6	0.8,0.2.0.2

With the weight vector and Equation (10), then the collective SVNN of the alternative $L_r(r = 1, 2, 3)$ can be obtained, which are listed as follows:

$$L_1 = \langle 0.5234, 0.2745, 0.4449 \rangle$$

$$L_2 = \langle 0.5721, 0.5435, 0.4671 \rangle$$

$$L_3 = \langle 0.7933, 0.2507, 0.1950 \rangle$$

According to Equation (6), we get $Q(L_r)$ as follows:

$$Q(L_1) = 0.6014$$

$$Q(L_2) = 0.5205$$

$$Q(L_3) = 0.7839$$

By comparing with Table 4, we can conclude that L1 and L3 are at minor risk, and L3 is in the best condition.

Table 13 | NVNN matrix of submarine pipeline

		L_1	L_2	L_3
$z_1(z_{11}, z_{12}, z_{13})$	$z_{11}\begin{pmatrix} z_{111}, z_{112}, z_{113}, \\ z_{114}, z_{115} \end{pmatrix}$	$\left\langle \begin{matrix} (0.3, 0.7, 0.2, 0.6, 0.6), \\ (0.2, 0.6, 0.8, 0.4, 0.5), \\ (0.8, 0.4, 0.9, 0.5, 0.9) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.7, 0.8, 0.8, 0.7, 0.8), \\ (0.6, 0.6, 0.4, 0.2, 0.4), \\ (0.3, 0.3, 0.3, 0.5, 0.6) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.7, 0.7, 0.9, 0.9, 0.6), \\ (0.3, 0.6, 0.2, 0.9, 0.8), \\ (0.3, 0.3, 0.1, 0.2, 0.3) \end{matrix} \right\rangle$
	$z_{12}(z_{121}, z_{122})$	$\left\langle \begin{matrix} (0.7, 0.5), \\ (0.2, 0.1), \\ (0.4, 0.6) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.5, 0.8), \\ (0.5, 0.2), \\ (0.5, 0.4) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.6, 0.7), \\ (0.6, 0.2), \\ (0.3, 0.4) \end{matrix} \right\rangle$
	z_{13}	$\langle 0.5, 0.6, 0.5 \rangle$	$\langle 0.5, 0.8, 0.5 \rangle$	$\langle 0.2, 0.4, 0.9 \rangle$
$z_2(z_{21}, z_{22}, z_{23}, z_{24}, z_{25})$		$\left\langle \begin{matrix} (0.7, 0.9, 0.4, 0.9, 0.8), \\ (0.2, 0.1, 0.2, 0.1, 0.5), \\ (0.3, 0.1, 0.1, 0.2, 0.3) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.7, 0.7, 0.7, 0.8, 0.7), \\ (0.3, 0.3, 0.3, 0.2, 0.3), \\ (0.3, 0.3, 0.3, 0.4, 0.3) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.8, 0.9, 0.7, 0.9, 0.8), \\ (0.1, 0.1, 0.1, 0.2, 0.2), \\ (0.1, 0.1, 0.1, 0.1, 0.4) \end{matrix} \right\rangle$
$z_3(z_{31}, z_{32})$		$\left\langle \begin{matrix} (0.8, 0.8), \\ (0.3, 0.3), \\ (0.3, 0.3) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.7, 0.5), \\ (0.6, 0.6), \\ (0.3, 0.5) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.8, 0.6), \\ (0.2, 0.2), \\ (0.3, 0.3) \end{matrix} \right\rangle$
$z_4(z_{41}, z_{42}, z_{43}, z_{44})$		$\left\langle \begin{matrix} (0.8, 0.9, 0.5, 0.3), \\ (0.3, 0.1, 0.3, 0.2), \\ (0.4, 0.2, 0.6, 0.9) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.8, 0.6, 0.7, 0.5), \\ (0.5, 0.2, 0.6, 0.8), \\ (0.3, 0.5, 0.3, 0.3) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.7, 0.4, 0.8, 0.9), \\ (0.2, 0.3, 0.2, 0.1), \\ (0.4, 0.7, 0.3, 0.1) \end{matrix} \right\rangle$
$z_5(z_{51}, z_{52}, z_{53}, z_{54}, z_{55})$	z_{51}	$\langle 0.3, 0.4, 0.7 \rangle$	$\langle 0.5, 0.5, 0.6 \rangle$	$\langle 0.8, 0.3, 0.1 \rangle$
	z_{52}	$\langle 0.5, 0.2, 0.3 \rangle$	$\langle 0.5, 0.9, 0.6 \rangle$	$\langle 0.9, 0.3, 0.2 \rangle$
	z_{53}	$\langle 0.4, 0.2, 0.7 \rangle$	$\langle 0.5, 0.9, 0.6 \rangle$	$\langle 0.8, 0.4, 0.2 \rangle$
	z_{54}	$\langle 0.5, 0.2, 0.3 \rangle$	$\langle 0.5, 0.4, 0.5 \rangle$	$\langle 0.9, 0.3, 0.2 \rangle$
	$z_{55}(z_{551}, z_{552})$	$\left\langle \begin{matrix} (0.7, 0.6), \\ (0.4, 0.1), \\ (0.4, 0.2) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.7, 0.6), \\ (0.7, 0.2), \\ (0.6, 0.6) \end{matrix} \right\rangle$	$\left\langle \begin{matrix} (0.8, 0.8), \\ (0.3, 0.2), \\ (0.2, 0.2) \end{matrix} \right\rangle$

Table 14 | E-value of submarine pipeline

First-grade	Weight	Second-grade	Weight	Third-grade	Weight
Pipeline corrosion	0.1937	External corrosion	0.5538	Environmental corrosion	0.2672
				Cathodic protection	0.0088
				Pipeline property	0.6204
				Stress corrosion	0.0616
				Number of years	0.0420
		Internal corrosion	0.0226	Fluid properties	0.3397
				Internal corrosion protection	0.6603
		Age and corrosion detection	0.4236		
Fatigue aging	0.0696	Pressure safety factor	0.0503		
		Pipe diameter	0.1290		
		Pipeline life	0.7362		
		Wave current scour	0.0371		
		Mitigation measures	0.0474		
Nature break forces	0.1070	Soil movement	0.0914		
		Extreme weather	0.9086		
Third-party damage	0.1364	Overburden condition	0.0114		
		Water activity level	0.3124		
		Preventive measures against damage	0.1073		
		Identification of the sea area around the pipeline	0.5689		
Misoperation	0.4932	Safety check	0.3554		
		Technological procedure	0.2001		
		Safety record	0.2071		
		Training situation	0.2001		
		Comprehensive quality of personnel	0.0373	Business capability	0.1734
				Sense of responsibility	0.8266

6.4. Suggestions

The leading cause of ship oil spill are as follows: In ship 1, the crews' responsibility factor and ship factor. In ship 2, crews' business skills and experience and natural environmental factors. In ship 3, crews' physical condition, staffing and training, and management supervision and inspection.

Except for ship factors, it is found that in the correlation analysis results of the three ships, the first and second factors are always the responsibility of the crew and the business skills and experience of the crew are among human factors. The responsibility index of the crew is always the biggest factor affecting the oil spill risk value. Therefore, strengthening the control of human factors has a significant effect on reducing the risk of oil spill. Shipping companies should strengthen the quality education of seafarers and require them to fulfill relevant obligations while on duty. Technical training and psychological quality training of the crew should be strengthened to increase their responsibility. The health status of the crew should be concerned to ensure the health of the crew from the aspects of mental health and physical health, to avoid the oil spill risk caused by the health of crew. In the ship factor, strengthen the maintenance of the ship to improve the technical state of the ship. Among the environmental factors in the port, the navigation command of ships in the port should be strengthened to clear the port in time. Meanwhile, navigable conditions in the port should be designated to strengthen real-time observation of changes in the marine environment. Among the management factors, we should strengthen the training and management of the crew, formulate a perfect safety management system for the ship company, and at the same time, the management should always perform the duties of supervision and inspection.

The leading cause of offshore oil platform oil spill are as follows: In P1, viscosity factor in oil characteristic element and coastal area category factor in oil spill location element. In P2, toxicity, persistence and flammability factors in oil characteristic elements. In P3, surface flow direction and wave height factors in hydrology element.

It is found that in the correlation analysis results of the three offshore oil platforms, oil spill factors are closely related to oil characteristics. In order to effectively reduce the risk of oil spill, operators must strictly implement operating procedures and make thorough drilling plans before drilling. The platform should be equipped with safe and effective blowout prevention equipment and good kill materials and well-control equipment. At the same time, it is necessary to provide professional and technical training to operators in key positions, adhere to the certification of the job, and establish a sound well-control management system. It should also strengthen drilling observation and detect problems on time, implement effective control according to correct shut-in procedures, and organize well killing servicing timely. Setting up a fire extinguishing system and providing portable fire extinguishers in key places, developing a rigorous oil spill contingency plan, and responding in the event of a blowout.

Third-party damage, erosion and suspension, natural disasters and corrosion are the main causes of submarine pipeline leakage accidents. In order to reduce the risk of oil spill in the submarine pipelines, first improve the design and installation level of the submarine pipelines, select high-quality materials, optimize pipeline design, and formulate the correct construction schemes, strict operation management and other comprehensive measures. Second, improve the ability of emergency response to oil spill events: improve the ability to predict oil spill point, oil spill volume, and oil spill drift path. and strengthen the allocation capacity of petroleum emergency equipment. Again, use online detection technology to prevent the oil spill of submarine pipelines. Through regular detection of the possible leakage potential points of submarine pipelines, and timely maintenance measures are taken to reduce the risk of oil spill. Finally, define the use function of the sea area to ensure that anchoring and fishing operations are prohibited in the submarine oil pipeline area, so as to reduce the risk of submarine oil pipeline leakage caused by external forces.

7. CONCLUSIONS

How to determine the influencing factors and their weights is the key and difficult part when dealing with the problem of the offshore oil spill. In this paper, a set of evaluation index system for ship oil spill, offshore oil platform oil spill and submarine pipeline oil spill is constructed, and an *n*-valued neutrosophic comprehensive evaluation model is built. In addition, entropy is used for calculating the weight, and the oil spill risk values of each sample can be calculated by the NVNWAA operator. Finally, the risk grades of each sample are analyzed and some suggestions are given. Compared with the literature (Zhang *et al.* 2016; Liu *et al.* 2017; Pan 2020), we use a neutrosophic number to represent the evaluation data, which can better reflect the integrity of the evaluation data, because it can represent not only the membership degree value and non-membership degree value, but also the uncertainty value, so that our evaluation results are more accurate. However, in the literature

(Zhang *et al.* 2016; Liu *et al.* 2017; Pan 2020), only membership degree value is used to represent the evaluation data, which will cause a little error in the experimental results. In addition, we use the entropy weight method to calculate the weight value, which is more accurate and objective, and can better explain the obtained results. The model provides the basis and support for the safety management of offshore oil spills, and can be used for risk assessment in the real environment while only adjusting the data according to the actual situation of the assessment object.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Baksh, A. A., Abbassi, R., Garaniya, V. & Khan, F. 2018 Marine transportation risk assessment using Bayesian network: application to Arctic waters. *Ocean Engineering* **159**, 422–436.

Chen, J. Q. & Ye, J. 2017 Some single-valued neutrosophic dombi weighted aggregation operators for multiple attribute decision-making. *Symmetry* **9** (82). doi:10.3390/sym9060082.

Fan, C. X. 2019 Correlation coefficients of refined-single valued neutrosophic sets and their applications in multiple attribute decision-making. *Journal of Advanced Computational Intelligence and Intelligent Informatics* **23** (3), 421–426.

Fan, C. X. & Ye, J. 2017 The cosine measure of refined-single valued neutrosophic sets and refined-interval neutrosophic sets for multiple attribute decision-making. *Journal of Intelligent & Fuzzy Systems* **33**, 2281–2289. doi:10.3233/JIFS-17270.

Fan, C. X., Fan, E. & Ye, J. 2018 The cosine measure of single-valued neutrosophic multisets for multiple attribute decision-making. *Symmetry-Basel* **10** (154). doi:10.3390/sym10050154.

Fan, C. X., Hu, K. L., Feng, S., Ye, J. & Fan, E. 2019 Heronian mean operators of linguistic neutrosophic multisets and their multiple attribute decision-making methods. *International Journal of Distributed Sensor Networks* **15** (4). doi: 10.1177/1550147719843059. journals.sagepub.com/home/dsn.

Jin, M. J., Shi, W., Yuen, K. F., Xiao, Y. & Li, K. X. 2019 Oil tanker risks on the marine environment: an empirical study and policy implications. *Marine Policy* 108–127. doi: 10.1016/j.marpol.2019.103655.

Lee, M. & Jung, J. Y. 2013 Risk assessment and national measure plan for oil and HNS spill accidents near Korea. *Marine Pollution Bulletin* **73** (l), 339–344.

Liu, J. Z., Wang, L. J., Ge, Y. M., Zhou, Y. & Sun, J. Y. 2017 Fuzzy comprehensive evaluation of oil spill risk in port area based on analytical hierarchy process. *Mavigation of China* **40** (3), 113–117.

Nevalainen, M., Helle, I. & Vanhatalo, J. 2016 Preparing for the unprecedented–Towards quantitative oil risk assessment in the Arctic marine areas. *Marine Pollution Bulletin* **114** (1), 3–15.

Özkan, U. 2016 Analysis of fire and explosion accidents occurring in tankers transporting hazardous cargoes. *International Journal of Industrial Ergonomics* **55**, 1–11.

Pan, Y. Y. 2020 *The Oil Spill Risk Assessment of Tankers in Shenzhen Port Based on Fuzzy Comprehensive Evaluate*. Dalian Maritime University, China.

Said, B., Deli, I. & Smarandache, F. 2015 N-valued interval neutrosophic sets and their application in medical diagnosis. *Critical Review*. doi:10.6084/M9.FIGSHARE.1502596.

Singh, A., Asmath, H., Chee, C. L. & Darsan, J. 2015 Potential oil spill risk from shipping and the implications for management in the Caribbean Sea. *Marine Pollution Bulletin* **93** (l–2), 217–227.

Smarandache, F. 1998 *Neutrosophy: Neutrosophic Probability, Set, and Logic*. American Research Press, Rehoboth, DE, USA.

Smarandache, F. 2013 n-valued refined neutrosophic logic and its applications in physics. *Progress in Physics* **4**, 143–146.

Smarandache, F. 2017 *Neutrosophic Perspectives: Triplets, Duplets, Multisets, Hybrid Operators, Modal Logic, Hedge Algebras and Applications*. PonsEditions, Bruxelles, Belgium, 323, pp. 115–123.

Sun, Y. & Han, H. 2010 Research of ship oil spill risk monitoring & evaluation system in Shanghai Yangshan Port water area. In: *International Conference on Networked Computing & Advanced Information Management*, pp. 412–416.

Wang, H., Smarandache, F., Zhang, Y. Q. & Sunderraman, R. 2010 Single valued neutrosophic, sets. *Multispace and Multi Structure* **4**, 410–413.

Wu, H. C. 2016 Research on ship risk assessment based on artificial neural network. *Automation & Instrumentation* **000** (008), 152–154.

Xiao, J. K., Yin, P. H. & Lin, J. G. 2002 An artificial neural network method for identification of oil spill risk degree in ship area. *Marine Environmental Science* **21** (4), 42–45.

Yan, C. & Ma, L. 2011 Evaluation of oil spill risk of inland river ships based on grey and fuzzy theory. *Ship Science and Technology* **1**, 113–117.

Ye, S. & Ye, J. 2014 Dice similarity measure between single valued neutrosophic multisets and its application in medical diagnosis. *Neutrosophic Sets and Systems* **6**, 48–53.

Ye, S., Fu, J. & Ye, J. 2015 Medical diagnosis using distance- based similarity measures of single valued neutrosophic multisets. *Neutrosophic Sets and Systems* **7**, 47–52.

Zadeh, L. A. 1965 Fuzzy sets. *Information and Control* **8** (3), 338–353.

Zhang, Q., Liu, L., Pan, B. Y., Dong, S. F., Dong, J. L. & Fan, C. 2016 Marine oil-spill pollution assessment model based on fuzzy comprehensive evaluation. *Marine Science* **40** (50), 97–102.

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