A quantitative approach for risk assessment of a ship stuck in ice in Arctic waters

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Arctic waters have historically been regarded as harsh environments owing to their extreme weather conditions and remoteness from land. The advantages of shorter sea routes and hydrocarbon energy exploitation have recently led to increased marine activities in such harsh environments. To ensure safe operation within the area, the potential risks of ship accidents, need to be systematically analyzed, assessed and managed along with the associated uncertainties. The treatment of epistemic uncertainty in the likelihoods of adverse events due to lack of knowledge and information should also be considered. This paper presents a Frank copula-based fuzzy event tree analysis approach to assess the risks of major ship accidents in Arctic waters, taking uncertainty into consideration. The quantitative approach includes four steps, namely, accident scenario modeling by an event tree model, probability and dependence analysis of the associated intermediate events, risk assessment with respect to the consequent outcome events. A major ship accident in Arctic waters - ships stuck in ice, is chosen as a case to interpret the modeling process of the approach proposed. Crews and ships owners can use such approach to defining risk control options that enable optimal risk mitigation. Maritime management may also benefit from better risk assessment.

Key works: Arctic waters, ship accidents, accident scenario analysis, ship stuck in ice, fuzzy-event tree analysis, Frank copula

List of abbreviations

ET	Event Tree
IE	Intermediate Event
MSC	Maritime Safety Committee
NSR	Northern Sea Route
OE	Outcome Event
IMO	International Maritime Organization
PMCC	Product-Moment Correlation Coefficient
SEQ	Sequence number
TFN	Triangular fuzzy number

1. Introduction

Recently, Arctic waters have become more accessible for marine activities due to the increased melting of the Arctic sea ice (Ho, 2010; Verny and Grigentin, 2009; Parsons et al., 2011; ABS, 2014). On the other hand, the northern sea route (NSR) through the Arctic sea is attractive because it offers a shorter transit than the traditional routes through Suez Canal or Panama Canal (Liu and Kronbak, 2010; Raza and Schøyen, 2014; Schøyen and Bråthen, 2011). Moreover, the polar areas are attractive for exploitation of the hydrocarbon resources. These advantages explain why marine activities in Arctic waters were gradually increasing in recent years (NSR, 2016). Nevertheless, these waters still share only a small amount of international shipping transits and lack of appropriate response capacity in case of emergency. The reason is that Arctic waters have historically been regarded as harsh environments, including extended sea ice, severe operating conditions, unpredictable weather changes, poorly charted waters, remoteness of the polar areas for marine activities, and an overall high degree of uncertainty regarding navigational environment conditions (Meng et al., 2016). The increasing ship traffic and exploitation in this area, the safety of marine activities and operations in such harsh environments, thus, becomes of great interest (MSC, 2014). Hence, there is a need for risk analysis of major ship accidents in Arctic waters.

The analysis of the risk associated with ship operations in ice-covered waters has obtained much attention from academic and industry (Afenyo et al., 2016; Afenyo et al., 2016; Canada, 1998; MSC, 2014; Arctic Council, 2009; Fu et al., 2015; Fu et al., 2016; Fu et al., 2016; Goerlandt et al., 2016; Khan et al., 2014; Kotovirta et al., 2009; Kum and Sahin, 2015; Liu et al., 2016; Marken et al., 2015; Montewka et al., 2015; Sørstrand, 2012; Valdez Banda et al., 2016; Valdez Banda et al., 2015). The 2009 Arctic marine shipping assessment report (Arctic Council, 2009) focused on the future scenarios development and environmental considerations of Arctic shipping. The international code for ships operating in polar waters (Polar Code) was adopted by the International Maritime Organization (IMO) during its 94th Maritime Safety Committee meeting (MSC, 2014). The polar code highlighted a comprehensive list of hazards for marine operations in Arctic waters, but it scantily elaborated on the risk influencing factors (RIFs) involved in some individual operations, or on the appropriate modeling techniques to be used for formal safety assessment(MSC, 2013). Besides, a few event-oriented models were proposed for the risk analysis of major operations in ice-covered waters. Khan et al. (Khan et al., 2014) proposed a transportation risk analysis framework for collision accidents in Arctic waters by using a Bayesian network model. Kum and Sahin (Kum and Sahin, 2015) used a fuzzy fault tree method considering some causal risk factors in human and management aspects, concerning collision and grounding accidents in Arctic waters. Marken et al. (Marken et al., 2015) conducted a delay risk analysis of ship sailing in the NSR by using a traditional Bow-tie diagram, integrated by fault tree analysis and event tree (ET) analysis. Valdez Banda et al. (Valdez Banda et al., 2016; Valdez Banda et al., 2015) presented a risk management model for the Finnish-Swedish Winter Navigation System, by incorporating formal safety assessment and a Bayesian network model. Goerlandt et al. (Goerlandt et al., 2016) carried out an analysis of winter operations in the Northern Baltic Sea involving icebreakers and assisted ships, pointing to various relationships between the ice feature and operational characteristics. Afenyo et al. (Afenyo et al., 2016; Afenyo et al., 2016) presented a model of oil spill accidents in ice-covered waters. Montewka et al. (Montewka et al., 2015) and Fu et al. (Fu et al., 2016) presented Bayesian networks models for analyzing ship performance in dynamic ice and predicting the probability of ships getting stuck in ice in the Northern Baltic Sea and NSR, respectively. These publications focus on major accidents of ship operations in ice-covered waters, such as collision (Goerlandt et al., 2016; Khan et al., 2014; Valdez Banda et al., 2016; Valdez Banda et al., 2015), grounding (Kum and Sahin, 2015; Valdez Banda et al., 2016; Valdez Banda et al., 2015), ship delay (Marken et al., 2015), oil spill (Afenyo et al., 2016; Afenyo et al., 2016; Marken et al., 2015) and ship besetting/stuck in ice (Fu et al., 2016; Fu et al., 2016; Montewka et al., 2015). However, this is still a limited amount of publications, compared with the studies of risk analysis of ship operations in open-water (Fu et al., 2016; Goerlandt and Montewka, 2015; Graziano et al., 2016; Hanninen et al., 2014; Li et al., 2012; Mazaheri et al., 2016; Mazaheri et al., 2015; Zhang et al., 2016; Zhang et al., 2013). Furthermore, very little research to date has focused on the risks of potential accident scenarios and undesirable consequences of ship operations in ice-covered waters (Kotovirta et al., 2009; Kubat et al., 2015).

The ET analysis is a distinct and graphically supported method used to develop a logical relationship between the events leading to an accident and estimated the level of risk associated (Ferdous et al., 2011; Huang, 2001; Zio, 2007). In an ET model, the event that generates the accident is named an initiating event, and the follow-up ones are termed intermediate events (IEs) or safety barriers (AIChE, 2000; Ferdous et al., 2011). The ET analysis represents the progression of the dichotomous conditions (e.g. success/failure or yes/no) of the initiating event onto the subsequent IEs all the way to the outcome events (OEs) of the accident sequence (AIChE, 2000; Andrews, 2000). In general, the ET analysis is used under two basic assumptions. First, the probability of occurrence of the events is assumed to be precisely known; in practice, this is often difficult to obtain due to imperfect or incomplete information (Chang et al., 2015; SRA, 2015) that leads to epistemic uncertainty in the ET probability values. The treatment of this kind of epistemic uncertainty associated with the probability of occurrence of events in an ET model – parameter uncertainty, can be of great importance, particularly in situations where little data and information are available, like for ship accidents in Arctic waters. Furthermore, the dependence of collected IEs in the ET model is also uncertain (Ferson S., 2004; Janbu, 2009). The impacts of the two different types of epistemic uncertainties, namely, parameter uncertainty and dependence uncertainty, must, thoroughly, be considered in the risk assessment process (Ferdous et al., 2011).

The objective of this paper is to develop an original Frank-copula based fuzzy-ET approach for quantitative risk assessment of ship accidents in Arctic waters, by investigating the probabilities of potential accident scenarios of a certain ship accident. The primary feature of the quantitative approach proposed is that it enables us to describe, measure and propagate the effects of parameter and dependence uncertainties in the ET model. Fuzzy sets are used to describe the former uncertainty in the situation of scarce and limited datasets for IEs. For the latter uncertainty, The Frank-copula is used to describe the interdependence between dependent events and make a precise calculation for the probability of OEs in the ET model. A major ship accident in Arctic waters – ship stuck in ice, is chosen as a case to interpret the approach. For this, this study provides an insight into the combined effects of the probability of occurrence and potential consequences of the ship becoming stuck in ice, and it properly distinguishes between different accident scenarios. The approach can assist in determining risk control options that enable optimal risk mitigation.

The remainder of the paper is structured as follows. Section 2 proposes an ET model for the risk analysis of a ship stuck in ice in Arctic waters. Section 3 describes the methods for epistemic and dependence uncertainties modeling and propagation. The modeling process and the obtained results are described in section 4, and discussed in section 5. Section 6 concludes the research findings.

2. Methods

Quantitative risk assessment of ship accidents in Arctic waters is a challenging problem, due to the limited data and information available. A quantitative method is proposed for analyzing accident risks in Arctic waters. The quantitative method can be used for estimating the risk of potential accident scenarios, with consideration of parameter and dependence uncertainties. The following sections describe the methodological framework adopted, along with the techniques of epistemic and dependence uncertainties modeling, and propagation.

2.1. Framework for quantitative risk assessment

The framework of the quantitative approach can be decomposed into four steps, as follows:

Step 1: ***Accident scenarios modeling***. Analyze accident scenarios of a typical ship accident in Arctic waters by developing an ET model, including an initiating event, IEs and OEs, logically connected in the resulting accident sequences (Ferdous et al., 2011; Marken et al., 2015).

Step 2: ***Probability analysis of the IEs***. Collect information and knowledge about the probability of occurrence of the IEs in the ET model proposed, from historical records, related literature and expert knowledge. Since information related to the initiating event and the IEs are uncertain for the ice-covered polar waters, an epistemic uncertainty modeling method- fuzzy sets (Zadeh, 1965) is used for collecting knowledge from the domain experts.

Step 3: ***Dependence analysis of the IEs***. A possibilistic approach is incorporated into the fuzzy-ET analysis for generating sample data, to analyze the dependence relationships between the connected IEs in the ET model. Correlation analysis is used for calculating the Pearson product-moment correlation coefficient (PMCC) of the connected IEs.

Step 4: ***Risk assessment***. According to the dependence based-fuzzy-ET analysis method, further, integrate Frank copula to conduct conjunction operations of the connected IEs in the ET model so as to calculate the probability of each accident sequence in the ET model. The probability of the OEs and the risk of the ship accident can also be calculated.

2.2. Fuzzy event tree analysis

Fuzzy sets are introduced by Zadeh (Zadeh, 1965) and have gained popularity in various fields, including reliability analysis and risk assessment (Sahin and Senol, 2015; Zio and Aven, 2013). The fuzzy set theory uses fuzzy numbers to capture the imprecision or vagueness in expert linguistic assessment. The membership function of a fuzzy number establishes a numerical relationship for uncertain values, ranging from 0 to 1. Triangular fuzzy numbers (TFNs) are flexible for uncertainty representation and propagation in the ET model (Baraldi and Zio, 2008; Ferdous et al., 2009; Ferdous et al., 2012).

Here, the TFN is a vector whose three elements range from 0 to 1 and are the lower bound, most likely, and upper bound values of the (uncertain) possibility/likelihood of occurrence for an event. In this paper, seven linguistic scales are used to describe expert knowledge relating to possibility values in the ET analysis. The linguistic terms and associated membership functions are reported in Table 1, taken from a study of transportation risk analysis in the Northern Sea Route (Marken et al., 2015).

Table 1

TFN of linguistic terms.

Linguistic terms	Membership function (TFNs)
Very low (VL)	(0, 0.025, 0.05)

Medium low (ML)	(0.045, 0.125, 0.2)
Low (L)	(0.15, 0.275, 0.4)
Medium (M)	(0.35, 0.5, 0.65)
High (H)	(0.6, 0.725, 0.85)
Medium high (MH)	(0.8, 0.875, 0.955)
Very high (VH)	(0.95, 0.975, 1)

The fuzzy set theory uses the fuzzy arithmetic operations based on the α-cut formulation to manipulate fuzzy numbers (Slier & Buckley, 2005). Suppose $\tilde{P}_A(p_{l_{\mathrm{A}}}, p_{m_{\mathrm{A}}}, p_{u_{\mathrm{A}}})$ is a TFN representing the possibility of the occurrence of event A; its rules of multiplication and complement operations are calculated as follows:

$$\lambda \times \tilde{P}_A = \lambda \times (p_{l_{\mathrm{A}}}, p_{m_{\mathrm{A}}}, p_{u_{\mathrm{A}}}) = (\lambda \times p_{l_{\mathrm{A}}}, \lambda p_{m_{\mathrm{A}}}, \lambda p_{u_{\mathrm{A}}}), \lambda > 0, \lambda \in R, \tag{1}$$

$$\overline{\tilde{P}_A} = 1 - (p_{l_{\mathrm{A}}}, p_{m_{\mathrm{A}}}, p_{u_{\mathrm{A}}}) = (1 - p_{l_{\mathrm{A}}}, 1 - p_{m_{\mathrm{A}}}, 1 - p_{u_{\mathrm{A}}}), \tag{2}$$

where Eq. (1) is a multiplication operation between $\tilde{P}_A$ and a crisp value, and $\overline{\tilde{P}_A}$ is the possibility of the occurrence of the complement event of event A.

The α-cut $\tilde{P}_{\mathrm{A}}^{\alpha}$ $(\alpha \in [0,1])$ of the TFN represents a fuzzy interval with $(1 - \alpha)\%$ degree of belief, which can be calculated as:

$$\tilde{P}_A^{\alpha} = [p_{l_A} + \alpha \times (p_{m_{\mathrm{A}}} - p_{l_A}), p_{u_{\mathrm{A}}} - \alpha \times (p_{u_{\mathrm{A}}} - p_{m_{\mathrm{A}}})], \tag{3}$$

The possibility mean of a TFN is used to calculate the defuzzification value (Kurano, 2006), which can be computed as:

$$\mathrm{P}_{A_{defuzzification}} = [p_{l_A} + \alpha \times (p_{m_{\mathrm{A}}} - p_{l_A})] + 2 * p_{m_{\mathrm{A}}} + [p_{u_{\mathrm{A}}} - \alpha \times (p_{u_{\mathrm{A}}} - p_{m_{\mathrm{A}}})]/4. \tag{4}$$

Suppose $\tilde{P}_B(p_{l_{\mathrm{B}}}, p_{m_{\mathrm{B}}}, p_{u_{\mathrm{B}}})$ is another TFN representing the possibility of the occurrence of event B. In case of event A and event B are independent, the possibility of their conjunction operation can be computed as the product of the possibilities of the two events, as follows:

$$\tilde{\mathrm{P}}(\mathrm{A\&B}) = \tilde{P}_A \otimes \tilde{P}_B = (p_{l_{\mathrm{A}}} \times p_{l_{\mathrm{B}}}, p_{m_{\mathrm{A}}} \times p_{m_{\mathrm{B}}}, p_{u_{\mathrm{A}}} \times p_{u_{\mathrm{B}}}). \tag{5}$$

The probability of the OEs resulting from the accident scenarios in the ET model can be calculated by multiplying the conditional probabilities of the associated IEs along the corresponding sequence with branches on the ET, from the initiating event A to the OEs. Traditional fuzzy arithmetic operations assume that the connected events (or IEs) are independent (Ferdous et al., 2011), the formulations for the fuzzy-ET analysis can, then, be developed as follows:

$$\tilde{P}_{SEQ_{i,j}}^{\alpha} = P_A \times \prod_{k=1}^{n} \tilde{P}_{IE_k}^{\alpha}, k = 1,2, \dots, n, \tag{6}$$

where, *k* is the IEs index; *n* refers to the number of IEs in the ET model; P_A refers to the probability of occurrence of the initiating event A; $\tilde{P}_{IE_k}^{\alpha}$ refers to the possibility of the *k*th IE in the α-cut; $\tilde{P}_{SEQ_{i,j}}^{\alpha}$ refers to the possibility of the sequence number (SEQ) j for the ith OE in the α-cut. Eq. (5) can also be seen as a multiplication operation between the probability of an initiating event A and the possibility of the corresponding $\tilde{P}^{\alpha}_{IE_k}$ in the SEQ j of the ith OE in the α-cut for calculating $\tilde{P}^{\alpha}_{SEQ_{i,j}}$.

The total possibility of OEs in the event model can be calculated as:

$$\tilde{P}^{\alpha}_{OEs} = \sum_{i=1}^{N} \tilde{P}^{\alpha}_{OE_i} = \tilde{P}^{\alpha}_{SEQ_{i,1}} \oplus \ldots \oplus \tilde{P}^{\alpha}_{SEQ_{i,j}}, i = 1,2,\ldots,N, j = 1,2,\ldots,M, \tag{7}$$

where, according to the definition of the ET model in section 2 (as shown in Fig. 1), i is the index of the OEs; N refers to the number of possible OE scenarios; j is the SEQ index; M refers to the SEQ number in the ET model; $\tilde{P}^{\alpha}_{OE_i}$ refers to the possibility of the ith OE in the α-cut; $\tilde{P}^{\alpha}_{SEQs}$ refers to the total possibility of OEs in the ET model in the α-cut. Eq. (6) can also be seen as an addition operation between the corresponding possibility of the ith OE in the α-cut ($\tilde{P}^{\alpha}_{OE_i}$) for calculating the total possibility $\tilde{P}^{\alpha}_{SEQs}$.

2.3. Dependence analysis

As mentioned in the previous section, the probability of occurrence of the events in the ET model is derived from multi-expert judgment, with the majority of them being possibilistic regarding linguistic terms, as illustrated in Table 1. A possibilistic approach integrating the Monte Carlo technique and fuzzy set theory (Baraldi and Zio, 2008; Terje Aven, 2014), is then used to propagate the uncertainty of information using the following three main steps:

- Select possibility value α and the corresponding cuts of the possibility distributions $\tilde{P}^{\alpha}_{IE_k}$ as the interval of possible values of the possibilistic variables *IE*$_k$.
- Compute the smallest and largest values of *IE*$_k$, denoted by $p^{\alpha}_{l_{IE_k}}$ and $p^{\alpha}_{u_{IE_k}}$ respectively, considering all values of the possiblilistic variables *IE*$_k$ in the α-cuts of their possibility distributions.
- Return to the first step and repeat for another α-cut; after having repeated the above two steps for all the α-cuts of interest, the fuzzy random realization can then be obtained as the sample data from which to calculate the correlation coefficient.

The PMCC is, then, used to estimate the correlation between two events, as follows (Freedman, 2010):

$$r_{PMCC} = \frac{\sum_{i=1}^{n}(a_i-\bar{a})(b_i-\bar{b})}{\sqrt{\sum_{i=1}^{n}(a_i-\bar{a})^2}\sqrt{\sum_{i=1}^{n}(b_i-\bar{b})^2}}, \tag{8}$$

where a = P(A) and b = P(B), a_i and b_i are two variables with random possibility distribution calculated by a possibilistic approach, and $\bar{a}$ and $\bar{b}$ are the means of the a_i and b_i, respectively.

The r_{PMCC} can describe the full range of dependencies ranging from -1 to 1, where 1 represents perfect dependence, $(0,1)$ represents positive dependence, 0 represents independence, $(-1,0)$ represents negative dependence and -1 represents opposite dependence.

According to the scale for categorizing the dependence between events proposed in Ferdous et al. (Ferdous et al., 2011), the dependence relationship between events can be further decomposed into six types, as follows:

- Perfect dependence. The value of the correlation coefficient between events is 1.000.
- Very strong dependence. The value of the correlation coefficient between events is between 0.800 and 0.995.
- Strong dependence. The value of the correlation coefficient between events is between 0.450 and 0.850.
- Weak dependence. The value of the correlation coefficient between events is between 0.150 and 0.500.
- Very weak dependence. The value of the correlation coefficient between events is between 0.005 and 0.200.
- Perfect independence. The value of the correlation coefficient between events is 0.000.

A significance test can be conducted to justify the degree of belief in the dependence between the data, which is calculated as:

$$t^{*} = r\sqrt{\frac{n-2}{1-r^{2}}}. \tag{9}$$

For Eq. (8), if $|t^{*}| > t_{\alpha/2}$, this indicates that the correlation of the data a_i and b_i is significant at level α; for example, if α is set at 0.01 or 0.05, this would correspond to a degree of belief in the results of 99% or 95%, respectively.

2.4. Frank copula-based conjunction operations

The fuzzy-ET analysis method above can be used to calculate the probability of each scenario and propagate uncertainty in the ET model. However, the independent assumption underlying IEs simplifies the actual dependence relationships between the connected IEs and, thus, adds dependence uncertainty. For this reason, an extended Frank copula-based conjunction operation mathematic is proposed to express this dependence, as discussed in this section.

Frank copula (Frank, 1979) is a formulation for expressing the correlation of events, which is defined by

$$C_{Frank}(a,b) = \log_{s}[1 + (s^{a} - 1)(s^{b} - 1)/(s - 1)], \tag{10}$$

$$\mathrm{s} = \tan(\pi(1 - \mathrm{r})/4), \mathrm{s} \geq 0, \tag{11}$$

where a and b refer to the probability of event A and event B, respectively; and $\mathrm{a} = \mathrm{P(A)}$ and $\mathrm{b} = \mathrm{P(B)}$, r is the correlation coefficient between $\mathrm{P(A)}$ and $\mathrm{P(B)}$. Perfect dependence arises in the limit as s tends to 0; opposite dependence arises when s goes to infinity, and independent corresponds to s equal to 1 (Ferson S., 2004).

In the Frank model of correlation between events, the probabilities of a conjunction of events A and B are given by the formula:

$$P_{Frank}(\mathrm{A\&B}) = \mathrm{Frank(a,b,r)} = \begin{cases} \min(a,b), if\ r = 1 \\ ab, if\ r = 0 \\ \max(1 + b - 1{,}0), if\ r = -1 \\ \log_{s}[1 + (s^{a} - 1)(s^{b} - 1)/(s - 1)], otherwise \end{cases}. \tag{12}$$

This function is continuous; a special case arises when *r* is +1, 0 or -1.

Since the ET model uses fuzzy numbers for the uncertain event probabilities, the Frank copula must be extended for using in the fuzzy-ET analysis. To do this, the monotonicity and bounds of Eq. (11) in each condition need to be analyzed. According to Eq. (10), if r is defined on the interval $(-1,0) \cup (0,1)$, the value of s belongs to the interval $(0,1) \cup (1,+\infty)$.

Suppose $\mathrm{f(a,b)} = (s^a - 1)(s^b - 1)/(s - 1)$ in the condition $\mathrm{r} \in (-1,0) \cup (0,1)$, the probability of the conjunction of event A and event B can be worked out using the formula:

$$F(\mathrm{s}) = \log_s[1 + \mathrm{f(a,b)}], a, b \in (0,1), \mathrm{s} \in (0,1) \cup (1,+\infty). \tag{13}$$

According to the monotonicity of the logarithmic function, if the base of the logarithmic function belongs to interval $(0,1)$ or $(1,+\infty)$, then the logarithmic function will be a decreasing or increasing function, respectively. Hence, $F(\mathrm{s})$ is a decreasing function when $\mathrm{s} \in (0,1)$, while $F(\mathrm{s})$ is an increasing function when $\mathrm{s} \in (1,+\infty)$.

On the other hand, the partial derivative of $\mathrm{f(a,b)}$ can be calculated as:

$$df(a,b)/da = [(s^b - 1) * s^a * \ln s]/s - 1, a, b \in (0,1), \mathrm{s} \in (0,1) \cup (1,+\infty). \tag{14}$$

In Eq. (14), if s is in interval $(0,1)$, then $(s^b - 1) < 0$, $s^a > 0$, $\ln s < 0$, $s - 1 < 0$ and the value of df/da will be negative, namely $df/da < 0$; if s is in interval $(1,+\infty)$, then $(s^b - 1) > 0$, $s^a > 0$, $\ln s > 0$, $s - 1 > 0$ and the value of df/da will be positive, namely $df/da > 0$. Similarly, since *a* and *b* are symmetrical in the $f(a,b)$, df/db is negative when $\mathrm{s} \in (0,1)$, while df/db is positive when $\mathrm{s} \in (1,+\infty)$.

It is clear that $\mathrm{Frank(a,b,r)}$ is a monotonic increasing function since both $F(\mathrm{s})$ and $f(a,b)$ are increasing functions when $\mathrm{s} \in (0,1)$, and decreasing functions when $\mathrm{s} \in (1,+\infty)$. In Eq. (13), if the value of the correlation coefficient r between events P(A) and P(B) is a constant, and the probabilities of the occurrence of events A and B (*a* and *b*) are intervals from fuzzy sets, the thresholds for the function can be calculated by using the lower and upper bounds of the probabilities of occurrence $(a_{min}, \mathrm{b}_{min})$ and $(a_{max}, \mathrm{b}_{max})$, respectively. By this way, the monotonic increasing copula function $\mathrm{Frank(a,b,r)}$, can be extended into fuzzy theory. If the input variables in the copula function $\mathrm{Frank(a,b,r)}$ are TFNs, this function can be formulated as follows:

$$\tilde{P}_{Frank}(\mathrm{A\&B}) = \left(P_{Frank}\left(p_{l_A}, p_{l_\mathrm{B}}\right), P_{Frank}\left(p_{m_\mathrm{A}}, \times\, p_{m_\mathrm{B}}\right), P_{Frank}\left(p_{u_\mathrm{A}}, p_{u_\mathrm{B}}\right)\right) \quad . \tag{15}$$

For two dependent IEs $\mathrm{IE_i}$ and $\overline{\mathrm{IE_j}}$, the conjunction operation of these two events can then be calculated as:

$$\tilde{\mathrm{P}}_{\mathrm{Frank}}\left(\mathrm{IE_i}\&\overline{\mathrm{IE_j}}\right) = \log_{\mathrm{s}_{\mathrm{IE_i}\&\overline{\mathrm{IE_j}}}}\left[1 + \left({\mathrm{s}_{\mathrm{IE_i}\&\overline{\mathrm{IE_j}}}}^{\mathrm{pl}^{\alpha}_{\mathrm{IE_i}}} - 1\right)\left({\mathrm{s}_{\mathrm{IE_i}\&\overline{\mathrm{IE_j}}}}^{\mathrm{pl}^{\alpha}_{\overline{\mathrm{IE_j}}}} - 1\right)/(\mathrm{s}_{\mathrm{IE_i}\&\overline{\mathrm{IE_j}}} - 1)\right], \tag{16}$$

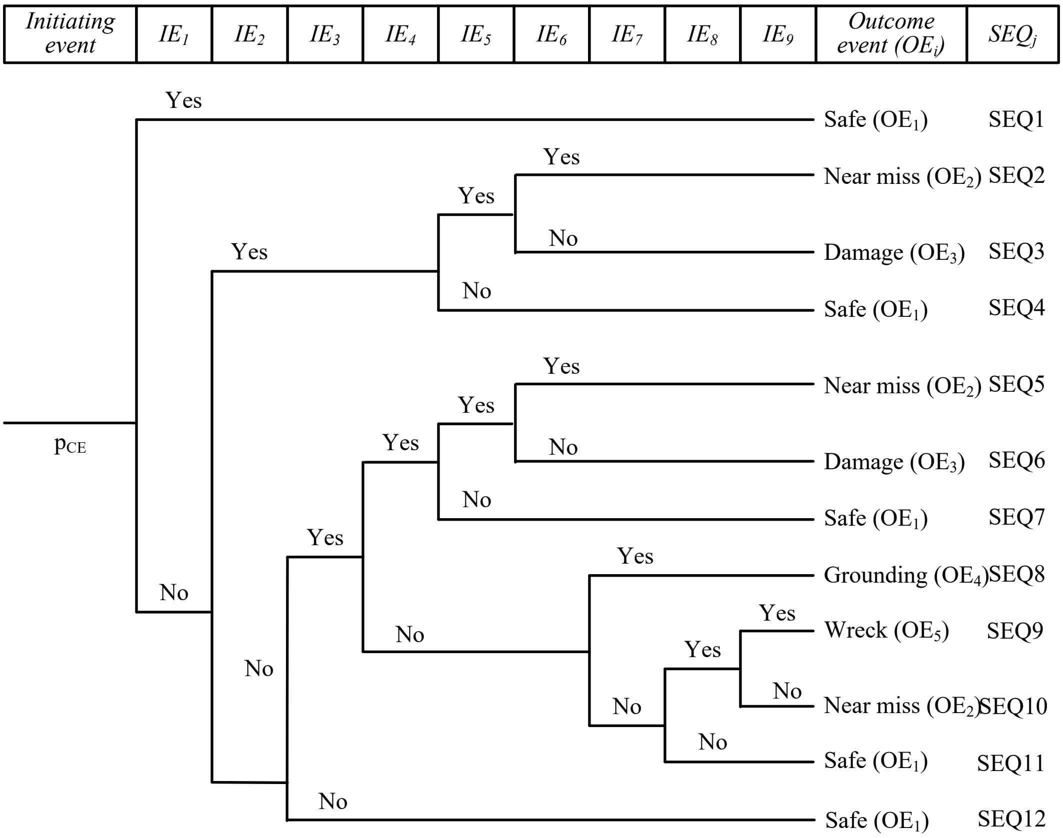
$$s_{\mathrm{IE_1}\&\overline{\mathrm{IE_2}}} = \tan\left(\pi\left(1 - r_{\mathrm{IE_1}\&\overline{\mathrm{IE_2}}}\right)/4\right). \tag{17}$$

3. Risk model

In this section, we present a risk model of a typical ship accident in Arctic waters – a ship stuck in ice. This is chosen as a case to interpret the quantitative approach proposed in section 2.

3.1. Accident scenarios modeling (step 1)

To model the ET of a ship stuck in ice, we consider the following technical and environmental factors: ice class of the ship, navigation operations, ice conditions, rescue ability, channel depth, meteorological environment and the ship's maintenance ability. The proposed ET model for the accident of a ship stuck in ice is depicted in Fig. 1. The considered risk factors are associated with the technical and environmental aspects of shipping, and organizational and human-related factors are beyond the scope of this paper and are not considered in the ET model.



IE_1: The stuck ship breaks the harsh sea ice by herself.
IE_2: There is nearby ship/icebreaker assistance.
IE_3: The stuck ship encounters fast moving ice.
IE_4: The ship is assisted by an icebreaker during a period of an uncontrolled drift.
IE_5: The ship collides with assisting ships (icebreakers) or objects.
IE_6: The damage extend of the ship is not significant.
IE_7: The depth of the fairway is less than the draught of the ship.
IE_8: The uncontrolled ship collides with ships or objects.
IE_9: The ship hull is breached upon collision with ships (icebreaking ships or icebreakers) or objects.

Fig. 1. An ET model for accident scenarios of a ship stuck in ice, including nine intermediate events (IEs), five outcome events (OEs) and twelve accident sequences; upper branch corresponds to the occurrence of the event, lower branch to nonoccurrence. SEQ = sequence number.

As shown in Fig. 1, the potential scenarios that can originate from the given initiating event - a ship stuck in ice - are described by nine IEs and five OEs, logically structured in twelve possible accident sequences on the basis of expert knowledge and related studies (Afenyo et al., 2016; Afenyo et al., 2016; Committee, 2014; Council, 2009; Fu et al., 2016; Fu et al., 2016; Goerlandt et al., 2016; Khan et al., 2014; Kotovirta et al., 2009; Kubat et al., 2015; Kum and Sahin, 2015; Marken et al., 2015; Montewka et al., 2015; Valdez Banda et al., 2016). The structure of the risk model is developed as an ET with nine IEs, as follows:

- IE_1: The stuck ship breaks the harsh sea ice by itself.

- IE_2: There is nearby ship/icebreaker assistance. There is available icebreakers or ice-going ships with a high ice class to assist the stuck ship in breaking up the harsh sea ice.
- IE_3: The stuck ship encounters fast moving ice. In some extreme weather conditions, ships may lose control and collide with ice floes or ice ridges. This event had happened and caused the wrecking of several ships in Arctic waters (Marchenko, 2011).
- IE_4: The ship is assisted by an icebreaker during a period of uncontrolled drift. Following the drift, icebreakers are available in some coastal areas and within the scope of research and rescue.
- IE_5: The ship collides with the assisting icebreaker. The forces of collision may lead to damage to the hull structure.
- IE_6: The damage extend of the ship is not significant.
- IE_7: The depth of the fairway is less than the draught of the ship. During an uncontrolled drift with the ice field, the ship may drift into shallow waters.
- IE_8: The uncontrolled ship collides with ships (icebreaking ships or icebreakers), an iceberg, or ice ridge ice.
- IE_9: The ship hull is breached in the collision accidents (Khan et al., 2014).

On the consequences of the ship accident following the development of the initiating event and possible IEs for the accident of a ship stuck in ice may lead to five major OEs, as follows:

- OE_1: Safe. The ship is released from the harsh sea ice and can continue its voyage.
- OE_2: Near miss. The ship sustains slight damages, which can be handled by the crew onboard. The ship can continue its voyage.
- OE_2: Damage. Damage occurs to the hull structure, which cannot be repaired by the crew on board. The ship is unable to continue and has to proceed to the nearest port, where the necessary repairs can be done.
- OE_4: Grounding. The uncontrolled ship runs aground and is unable to continue its voyage.
- OE_5: Wreck. The hull is breached, and the ship cannot continue its voyage.

As shown in Fig. 1, the ship will be safe (OE_1) in SEQ 1, 4, 7 and 11; the ship will have a near miss (OE_2) in SEQ 2, 5 and 10, suffering slight damages on board; the ship will be damaged (OE_3) in SEQ 3 and 6, because of collision with objects; the ship will be grounded (OE_4) in SEQ 8, if the water depth is deficient; the ship will wreck (OE_5) in SEQ 9, owing to a significant breach in the hull structure after collision.

3.2. Probability analysis of the IEs (step 2)

The data and information used for probability analysis of the IEs in ET model are elicited from seven experts, including one captain, four professors, and two senior researchers. Their detail information is listed as follows:

- Expert A: An associate professor engaged in risk management of ship operations in ice-covered waters since more than five years, from the National Engineering Research Center for Water Transport Safety and the Wuhan University of Technology.
- Expert B: A professor engaged in navigation safety in polar waters since more than twenty years, from

School of Navigation of the Wuhan University of Technology.

- Expert C: An associate professor engaged in safety management of ship accidents system since more than five years, from the National Engineering Research Center for Water Transport Safety and the Wuhan University of Technology.
- Expert D: A specialist research scientist engaged in safety management and risk assessment of ship operations in harsh environments, from the Finnish Geospatial Research Institute.
- Expert E: An associate professor engaged in navigation safety in polar waters since more than a decade, from Shanghai Maritime University, also engaged as a second officer on board.
- Expert F: A senior researcher engaged in security management of ship operation in polar waters more than fifteen years, from China Classification Society Certification Company Shanghai Branch.
- Expert G: A senior captain with more than fifteen years' navigation experience in ice-covered waters, from the Polar Research Institute of China.

The linguistic judgments of the seven experts are given in Table 2, concerning the linguistic terms of Table 1. As shown in Table 2, experts' linguistic judgments as to the likelihood of various IEs are presented. Since these experts have difference working experiences and stand for different stakeholders, their opinions for several IEs are different. Some experts are negative for the undesired events. For example, the judgment of expert F for the IEs is more cautious compared to the other experts. We will analyze these experts' judgments individually so as to make a comprehensive analysis.

Table 2

Experts' linguistic judgments as to the likelihood of various IEs.

IE_s	Expert A	Expert B	Expert C	Expert D	Expert E	Expert F	Expert G
IE_1	ML	VL	L	M	L	L	M
IE_2	H	VH	M	H	H	H	L
IE_3	L	MH	MH	M	M	H	MH
IE_4	VL	ML	L	H	M	ML	ML
IE_5	ML	VL	L	VL	VL	M	ML
IE_6	L	VL	VL	M-H	ML	L	VL
IE_7	ML	VL	VL	ML	L	H	VL
IE_8	H	ML	M	M	MH	M	ML
IE_9	M	H	H	ML	L	MH	M

Use Eq. (3) to calculate the TFNs of the IEs from experts' judgment at 95% degree of belief (α=0.05). The TFNs in the α-cuts are listed in Table 3, which will be used in the subsequent dependence analysis, scenario analysis, and risk assessment.

Table 3

TFNs from experts' judgment for the IEs at 95% degree of belief (α=0.05).

IE$_s$	Expert A	Expert B	Expert C	Expert D	Expert E	Expert F	Expert G
IE$_1$	(0.049,0.125,0.196)	(0.001,0.025,0.049)	(0.156,0.275,0.394)	(0.358,0.5,0.643)	(0.156,0.275,0.394)	(0.156,0.275,0.394)	(0.358,0.5,0.643)
IE$_2$	(0.606,0.725,0.844)	(0.951,0.975,0.999)	(0.358,0.5,0.643)	(0.606,0.725,0.844)	(0.606,0.725,0.844)	(0.606,0.725,0.844)	(0.156,0.275,0.394)
IE$_3$	(0.358,0.5,0.643)	(0.804,0.875,0.951)	(0.804,0.875,0.951)	(0.358,0.5,0.643)	(0.358,0.5,0.643)	(0.606,0.725,0.844)	(0.804,0.875,0.951)
IE$_4$	(0.001,0.025,0.049)	(0.049,0.125,0.196)	(0.156,0.275,0.394)	(0.606,0.725,0.844)	(0.358,0.5,0.643)	(0.049,0.125,0.196)	(0.049,0.125,0.196)
IE$_5$	(0.358,0.5,0.643)	(0.001,0.025,0.049)	(0.156,0.275,0.394)	(0.00,0.025,0.049)	(0.001,0.025,0.049)	(0.358,0.5,0.643)	(0.358,0.5,0.643)
IE$_6$	(0.156,0.275,0.394)	(0.001,0.025,0.049)	(0.001,0.025,0.049)	(0.179,0.2625,0.346)	(0.049,0.125,0.196)	(0.156,0.275,0.394)	(0.001,0.025,0.049)
IE$_7$	(0.049,0.125,0.196)	(0.001,0.025,0.049)	(0.001,0.025,0.049)	(0.049,0.125,0.196)	(0.156,0.275,0.394)	(0.606,0.725,0.844)	(0.001,0.025,0.049)
IE$_8$	(0.606,0.725,0.844)	(0.049,0.125,0.196)	(0.049,0.125,0.196)	(0.358,0.5,0.643)	(0.804,0.875,0.951)	(0.358,0.5,0.643)	(0.049,0.125,0.196)
IE$_9$	(0.358,0.5,0.643)	(0.606,0.725,0.844)	(0.606,0.725,0.844)	(0.049,0.125,0.196)	(0.156,0.275,0.394)	(0.804,0.875,0.951)	(0.358,0.5,0.643)

3.3. Dependence analysis of the IEs (step 3)

To undertake this, we use the probability of occurrence of the IEs derived from the seven expert judgments to calculate the probability of the corresponding complement events for Eq. (3). For each of the seven expert judgments, the possibilitic approach is applied as follows:

(1) Set the possibility value α=0 and the corresponding cuts of the possibility distribution $\tilde{P}_{IE_k}^{\alpha=0}$ as the intervals of possible values of the possibilistic variables *IE$_k$* $(k = 1,2, \ldots, n)$. In this ET model of Fig. 1, the number of the probabilities of the IEs *n* is 12.

(2) Compute the smallest $(p_{l_{IE_k}})$ and largest $(p_{u_{IE_k}})$ values in its α-cut intervals $\left[p_{l_{IE_k}}, p_{u_{IE_k}}\right]$ (calculated based on Eq. (3) for 1000 Monte Carlo application sampled from a uniform distribution.

(3) Return to the first step and repeat for another α value (here ten α-cuts, for α=0.1:0.1:1).

Random realization can, then, be obtained by sampling the occurrence of each event 70,000 times. This is done in order to calculate the correlation coefficients of the events. The results of the PMCC and associated significance tests are shown in Table 4, as based on Eq. (8) and Eq. (9). The dependence relationships between connected IEs in the ET model are also depicted in Table 4.

Table 4

Product-moment correlation coefficients (r_{PMCC}) between the connected IEs in the ET model.

Events		r_{PMCC}	Dependence relationship	Events		r_{PMCC}	Dependence relationship
IE_2	IE_3	-0.519**	Negative, strong dependence	$\overline{\mathrm{IE}_1}$	IE_2	0.658**	Positive, very strong dependence
	$\overline{\mathrm{IE}_3}$	0.519**	Positive, strong dependence		$\overline{\mathrm{IE}_2}$	-0.658**	Negative, very strong dependence
IE_2	IE_5	0.475**	Positive, weak-strong dependence	$\overline{\mathrm{IE}_2}$	IE_3	0.288**	Positive, weak dependence
	$\overline{\mathrm{IE}_5}$	-0.475**	Negative, weak-strong dependence		$\overline{\mathrm{IE}_3}$	-0.288**	Negative, weak dependence
IE_3	IE_4	-0.689**	Negative, strong dependence	$\overline{\mathrm{IE}_4}$	IE_7	0.066**	Positive, very weak dependence
	$\overline{\mathrm{IE}_4}$	0.689**	Positive, strong dependence		$\overline{\mathrm{IE}_7}$	-0.066	Negative, very strong dependence
IE_5	IE_6	0.203**	Positive, weak dependence	$\overline{\mathrm{IE}_7}$	IE_8	-0.424**	Negative, weak dependence
	$\overline{\mathrm{IE}_6}$	-0.203**	Negative, weak dependence		$\overline{\mathrm{IE}_8}$	0.424**	Positive, weak dependence
IE_8	IE_9	-0.464**	Negative, weak-strong dependence				
	$\overline{\mathrm{IE}_9}$	0.464**	Positive, weak-strong dependence				

**. Correlation is significant at the 0.01 level (2-tailed).

As shown in Table 4, the dependence relationships between the most of the connected IEs are significant since the correlation coefficients (r_{PMCC}) are more than 0.2, except the r_{PMCC} between $\overline{\mathrm{IE}_4}$ and $\mathrm{IE}_7/\overline{\mathrm{IE}_7}$. Hence, we use Eq. (16) and Eq. (17) to calculate the conjunction operations for these couples of connected IEs. The dependence relationships between $\overline{\mathrm{IE}_4}$ and $\mathrm{IE}_7/\overline{\mathrm{IE}_7}$ are neglected in this paper, and a traditional formula – Eq. (5) are used to calculate the conjunction operations for these two conditions.

4. Results of risk assessment

4.1. Probability of the accident scenarios

The probability of the initiating event for a ship stuck in ice is set to a crisp of 0.02, based on our earlier work (Fu et al., 2016). Use the TFNs of the IEs listed in Table 3 to calculate the probability of the accident scenarios in the ET model, according to Eq. (6), (16) and (17). Then, use Eq. (4) to calculate the defuzzification values for each sequence. The sequence probability results for the twelve sequences, based on the seven experts' judgments, are listed in Table 5.

Table 5

Resulting defuzzification numbers for each sequence from the seven experts' judgments in the ET model proposed for the accident of a ship stuck in ice.

SEQ	Expert A	Expert B	Expert C	Expert D	Expert E	Expert F	Expert G
1	2.48E-03	5.00E-04	5.50E-03	1.00E-02	5.50E-03	5.50E-03	1.00E-02
2	2.06E-03	2.04E-05	7.86E-05	6.39E-05	5.00E-05	1.77E-03	6.48E-05
3	4.64E-03	4.73E-04	1.95E-03	1.40E-04	2.41E-04	3.92E-03	1.57E-03
4	7.23E-03	1.86E-02	6.38E-03	7.89E-03	1.10E-02	6.32E-03	2.21E-03
5	1.13E-05	4.94E-08	1.59E-05	7.06E-06	4.04E-06	5.51E-05	1.42E-05
6	2.22E-05	9.69E-07	3.35E-04	1.51E-05	1.83E-05	1.09E-04	2.99E-04

7	4.86E-05	5.08E-05	1.39E-03	1.00E-03	1.02E-03	2.41E-04	5.18E-04
8	1.13E-05	2.05E-06	5.84E-05	1.65E-04	3.49E-04	2.62E-04	2.71E-05
9	8.48E-04	3.70E-05	4.32E-04	3.34E-05	2.59E-04	3.90E-04	3.31E-04
10	1.13E-03	2.24E-05	2.54E-04	2.57E-04	8.23E-04	9.95E-05	4.51E-04
11	9.37E-04	3.96E-04	4.54E-03	3.55E-04	2.27E-04	5.59E-04	5.18E-03
12	2.44E-03	8.11E-05	9.55E-04	1.28E-03	1.96E-03	1.13E-03	9.55E-04

4.2. Probability of the outcome events

The probabilities of the OEs are calculated using Eq. (7), by multiplying the probability of the initiating event A with the total probabilities for the consequent scenarios:

$$P_{OE_1} = P_{SEQ_1} + P_{SEQ_4} + P_{SEQ_7} + P_{SEQ_{11}} + P_{SEQ_{12}}, \tag{18}$$

$$P_{OE_2} = P_{SEQ_2} + P_{SEQ_5} + P_{SEQ_{10}}, \tag{19}$$

$$P_{OE_3} = P_{SEQ_3} + P_{SEQ_6}, \tag{20}$$

$$P_{OE_4} = P_{SEQ_8}, \tag{21}$$

$$P_{OE_5} = P_{SEQ_9}. \tag{22}$$

According to Eq. (18) ~ (22), the resulting defuzzification numbers of the OEs provided by the seven experts' judgments are depicted in Fig, 2.

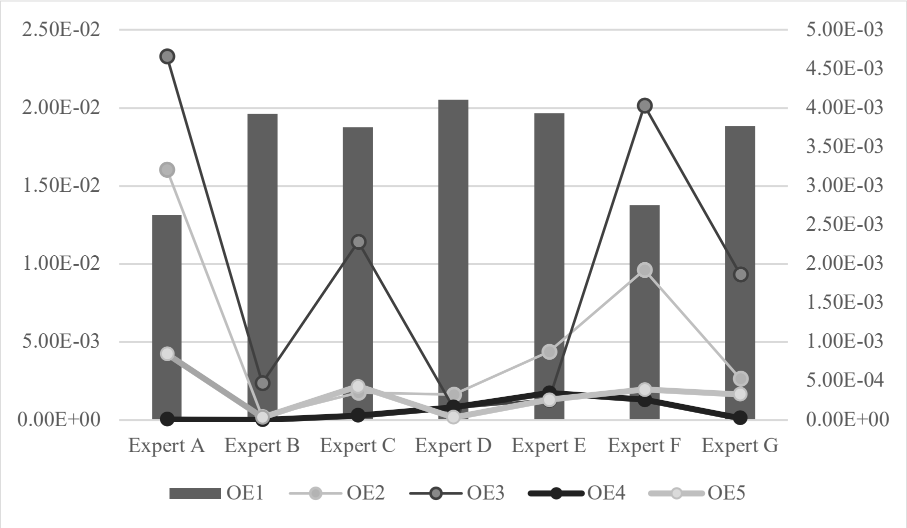


Fig. 2. Resulting defuzzification numbers of the OEs according to seven experts' judgments in the ET model proposed for the accident of a ship stuck in ice.

As shown in Fig. 2, the grey bar refers to the probability of the safe scenario - OE_1 from the seven experts' judgment, using the left vertical axis as a coordinate. The four lines use the right vertical axis as a coordinate for representing the hazardous scenarios in the ET model. The fine grey line refers to the probability of the OE_2, the fine black line refers to the probability of the OE_3; the bold black line refers to the probability of the OE_4; and the bold gray line refers to the probability of the OE_5. The ranking of the resulting probability of the OEs from the seven experts' judgments can be obtained, as follows:

- Expert A: OE$_1$> OE$_3$>OE$_2$>OE$_5$>OE$_4$,
- Expert B: OE$_1$> OE$_3$>OE$_2$>OE$_5$>OE$_4$,
- Expert C: OE$_1$> OE$_3$>OE$_5$>OE$_2$>OE$_4$,
- Expert D: OE$_1$> OE$_2$>OE$_4$>OE$_3$>OE$_5$,
- Expert E: OE$_1$> OE$_2$>OE$_4$>OE$_3$=OE$_5$,
- Expert F: OE$_1$> OE$_3$>OE$_2$>OE$_5$>OE$_4$,
- Expert G: OE$_1$> OE$_3$>OE$_2$>OE$_5$>OE$_4$.

According to the above rankings from the seven experts, it can be seen that OE$_1$ and OE$_4$ are seen both as the most likely and most unlikely OE$_s$ respectively for a ship stuck in ice; OE$_3$ is the second most likely to occur; OE$_2$ is the third most likely; finally, OE$_5$ is seen as the least likely to occur, by the majority of the experts' judgments. OE$_1$ is considered by far the most likely OE by all seven experts, with probabilities approximately around 10^{-2}; OE$_3$ is considered the second likely OE by five experts' judgments, with probabilities ranging between 2.59E-04 and 4.66E-0; OE$_2$ is considered the third likely OE by four experts' judgments, with probabilities ranging between 1.55E-04 and 1.87E-03; OE$_5$ is considered the fourth likely OE by four experts' judgments, with probabilities ranging between 3.34E-05 and 8.48E-04; OE$_4$ is considered the most unlikely OE by five experts' judgments, with probabilities ranging between 2.05E-06 and 3.49E-04.

This ranking (OE$_1$> OE$_3$>OE$_2$>OE$_5$>OE$_4$) is in accordance with the resulting average values of the probability of the OEs provided by the seven experts. As shown in Fig. 3, it can be discerned that OE$_1$ and OE$_4$ are seen both as the most likely and most unlikely OE$_s$ for the accident of a ship stuck in ice, with probabilities 1.78E-02 and 1.25E-04, respectively; OE$_3$ is the second most likely to occur with probability 1.96E-03; OE$_2$ is the third most likely with probability 1.25E-04; and finally, OE$_5$ is seen as the least likely to occur with probability 3.33E-04.

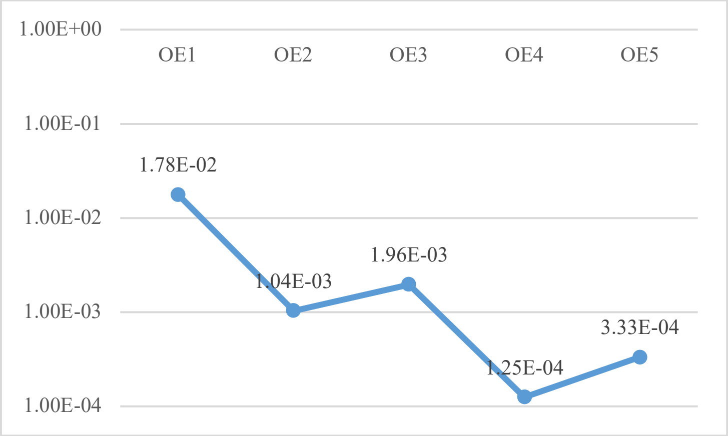


Fig. 3. The average values of the probability of the OEs in the ET model proposed for the accident of a ship stuck in ice.

The results obtained in the course of the presented study are compared with the similar studies conducted for the Northern Baltic Sea, see for example (Valdez Banda et al., 2016; Valdez Banda et al., 2015). The results of the probability of occurrence for the undesired events in this paper are between 10^{-5} and 10^{-3}, and these values are comparable to those characterizing maritime transportation systems operating in ice-covered waters of the Northern Baltic Sea . For example, the probability of occurrence of the damage event approximately equals to 10^{-4}. However, the resulting probability of occurrence for the grounding event in (Valdez Banda et al., 2015) is less than 10^{-4}, which is lower than the corresponding result for the OE_4 with the value being 1.25E-04, as presented in Fig. 3. This difference is due to the diverse environment conditions considered.

5. Discussion

Risk assessment of ship accidents in Arctic waters is a high concern issue in the marine industry with high uncertainty. The quantitative approach presented here shows a strong prediction power of the probability of ship stuck in ice in the current case study, in the absence of high-quality data in Arctic waters. The application of expert judgment in the proposed approach makes a supplement for such kind of data problem. However, it is difficult to judge the correction of the collected information for the disagreements among experts, which are influenced by complex factors, such as research background, status (stakeholder or not), personality (conservative or optimistic), working experience, etc. We intend to collect and analyze more expert judgments in the future.

The proposed ET model clearly depicts the IEs, scenarios and OEs in a figure for the initiating event of a ship stuck in ice in Arctic waters. If the conditions of some IEs are changed, we can see the new sequences through ET figure. Also, the risk of multiple scenarios of a ship stuck in ice can be calculated respectively, so that we can quickly find the worst scenario and make associated risk control options considering corresponding IEs.

Besides, both epistemic and dependence uncertainties in the quantitative risk assessment have been handled regarding the mathematical forms of fuzzy sets and Frank copula methods. The Frank copula based-ET analysis is a useful method that enables description and propagation the effects of uncertainties. Some other copula functions may be better than the Frank copula, but it is difficult to make a comparison the limited objective data. If high-quality data can be obtained, I would like to conduct further studies.

6. Conclusions

In this paper, a quantitative approach is proposed to analyze risks for ship accidents in Arctic waters. The occurrence probabilities of the initiating event and intermediate events are extracted from expert knowledge, and the probabilities of potential outcome events are computed. Fuzzy set theory and Frank copula are incorporated into the ET model to handle the parameter uncertainty in the probability values and the dependence uncertainty between dependent events, respectively. Additionally, a possibilistic approach integrating Monte Carlo simulation and fuzzy set theory is used to calculate the correlation relationship between events regarding linguistic terms. A typical event for ship operations in Arctic waters- ship stuck in ice is chosen as a case to interpret the approach proposed. The results show that the risk for ships stuck in ice in Arctic waters is comparable to that of maritime transportation systems operating in the Northern Baltic Sea. Through the case study analysis, the presented approach can be considered an appropriate approach for predicting the probability of the consequence of a ship getting stuck in ice.

The proposed risk approach enables to predict the risk for a ship stuck in ice in Arctic waters and also enables one to describe, measure and propagate the effects of uncertainties. Moreover, the approach provides an insight into the combined effects of the probability of occurrence and potential consequences of ship accidents. This study can assist the management of accident prevention or a ship's crew in planning and conducting an actual sea passage through Arctic waters.

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