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

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ABSTRACT

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.

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

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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.

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and industry (Afenyo et al., 2016a,b; Canada Transport, 1998; MSC, 2014; Arctic Council, 2009; Fu et al., 2015, 2016a,b; 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., 2015, 2016). 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. (2014) proposed a transportation risk analysis framework for collision accidents in Arctic waters by using a Bayesian network model. 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. (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. (2015, 2016) 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. (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. (2016a,b) presented a model of oil spill accidents in ice-covered waters. Montewka et al. (2015) and Fu et al. (2016b) 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., 2015, 2016), grounding (Kum and Sahin, 2015; Valdez Banda et al., 2015, 2016), ship delay (Marken et al., 2015), oil spill (Afenyo et al., 2016a,b; Marken et al., 2015) and ship besetting/stuck in ice (Fu et al., 2016a,b; 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., 2016c; 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., 2013, 2015). 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 and Dunnett, 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 et al., 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

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