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Towards a probabilistic model for predicting ship besetting in ice in Arctic waters

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ABSTRACT

Recently, the melting of sea ice due to global warming has made it possible for merchant ships to navigate through Arctic Waters. However, Arctic Marine Transportation System remains a very demanding, dynamic and complex system due to challenging hydro-meteorological conditions, poorly charted waters and remoteness of the area resulting in lack of appropriate response capacity in case of emergency. In order to ensure a proper safety level for operations such as ship transit within the area, a risk analysis should be carried out, where the relevant factors pertaining to a given operation are defined and organized in a model. Such a model can assist onshore managers or ships' crews in planning and conducting an actual sea passage through Arctic waters. However, research in this domain is scarce, mainly due to lack of data. In this paper, we demonstrate the use of a dataset and expert judgment to determine the risk influencing factors and develop a probabilistic model for a ship besetting in ice along the Northeast Passage. For that purpose, we adopt Bayesian belief Networks (BBNs), due to their predominant feature of reasoning under uncertainty and their ability to accommodate data from various sources. The obtained BBN model has been validated showing good agreement with available state-of-the-art models, and providing good understanding of the analyzed phenomena.

1. Introduction

The melting of the Arctic sea ice due to global warming has enabled voyages through Arctic waters [1–3]. With the opening of Arctic waters, the frontier of exploration of hydrocarbon resources can be pushed significantly northern, and also the existing trading routes between Europe and the Far East may change. The Northeast Passage offers a shorter and faster transit compared with the traditional Suez Canal or Panama Canal [4,5]. According to statistics from the Northern Sea Route (NSR) information office [6], there were 211 transits between 2011 and 2014, as shown in Fig. 1. The main ship types were oil and chemical tankers, as well as general cargo ships. Among these, two oil tankers “Marilee” and “Palva” crossed this route eastbound en-route to Incheon and Daesan ports in Korea, respectively, during the summer of 2012 [6]. Additionally, a general cargo ship “Yong Sheng” successfully transited the route westbound from Taicang in China to Rotterdam in Netherlands in the summer of 2013 [6,7].

Due to these new routes that are emerging, the safety of shipping and other maritime operations in Arctic waters has become of global interest. As a result, an international code for ships operating in polar waters (the Polar Code) was adopted by the International Maritime Organization in 2014, during its 94th Maritime Safety Committee (MSC) meeting [8], following a decade of discussion and deliberation. The Polar Code is expected to enter into force on 1 January 2017, to address all relevant issues pertaining to ships operating in waters surrounding the two poles, such as their design, construction, equipment, operation, training, search and rescue, and environmental protection, see for example [8]. Potential navigational hazards in Arctic waters have also been provided in this regulation, such as ice, low temperature, high latitude, remoteness and possible lack of accurate and complete hydrographic data and information, lack of suitable emergency response equipment and rapidly changing and severe weather conditions. However, the code is flexible in relation to determining the influencing factors for a specific operation, or the appropriate

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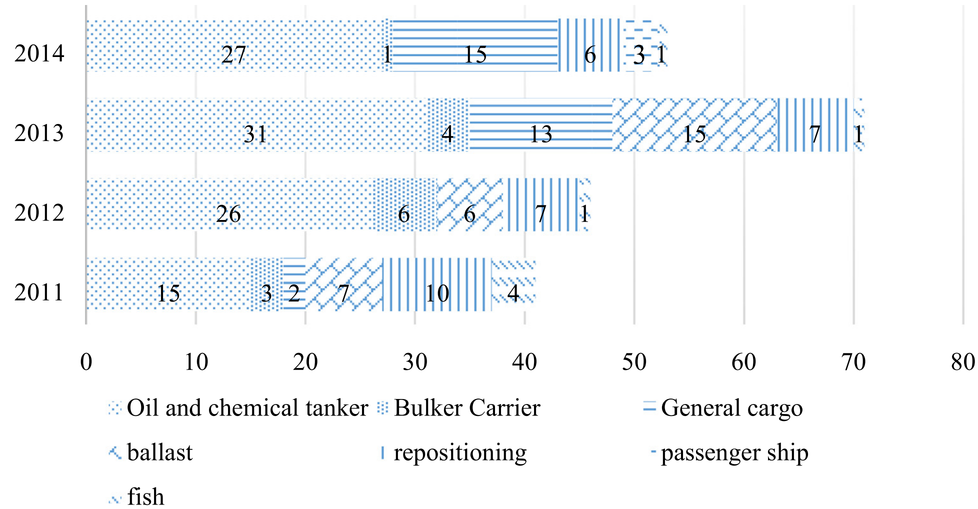

Fig. 1. Transit in NSR from 2011 to 2014.

modeling techniques for risk assessment. One of the major operational risks for ice navigation is associated with a ship becoming beset in ice [9–14], which may result in a myriad of consequences, including, but not limited to, uncontrolled ship drift, listing, hull damages including plate breaching, and sinking in the worst case. In case the risk of a ship stuck in ice is acceptable, the operations can be safely carried out. However, if the risk goes beyond the unacceptable level, the safe operations may be at stake, therefore efficient risk control options (RCOs) may be required to ensure safety. In order to quantify the risk, an appropriate risk model of a ship stuck in ice during Arctic transit is required. Since the risk models are developed for a specific purpose and usually have limited scope, there exists no risk model for a ship stuck in Arctic ice accident. Thus, the main aim of this paper is to develop such a model, utilizing experts' knowledge, available historical environmental data and navigational data obtained from a merchant voyage in Arctic waters.

A large body of knowledge exists on ship performance in ice-covered waters, which can be helpful in determining the relevant factors for the risk model presented here. For instance, the work on ice-induced load on ship hull can provide insight in the relationship between the parameters of ice cover and extent of damage that may be expected, see for example [15,16]. Likewise, an approach to determine the safe speed in Arctic ice, which will not result in hull damage, based on observed ice feature is proposed by Transport Canada [17] called "egg regulations", a structural equation modeling is proposed for determining the dependence relationships of the risk influencing factors (RIFs) in Arctic Marine Transportation System [18]. Moreover, a few event-oriented models have been proposed in recent years to quantify the major navigational risks in ice-covered waters. Khan et al. [19] proposed a transportation risk analysis framework for Arctic waters by using a BN method. Kum et al. [20] used a fuzzy fault tree method considering some causal risk factors in human and management aspects with reference to collision and grounding accidents in Arctic waters. Marken et al. [21] conducted a delay risk analysis of ship sailing in the NSR by using a traditional Bow-tie diagram, integrated by fault tree and ET analyses. Afenyo et al. [22] discussed the transport of oil spills in ice-covered water. Montewka et al. [13,14] analyzed ship performance in dynamic ice and predicted the probability of a ship stuck in ice in the Northern Baltic Sea. Valdez Banda et al. [23,24] conducted a risk assessment for winter navigation systems in the Northern Baltic Sea, providing insights into the relevant risk factors. Goerlandt et al. [25] 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. Various RIFs pertaining to ship performance and environment are considered in these models; however, they are to a large extent developed with the use of subjective judgment as a main source of background knowledge, and the uncertainty associated with these models is rarely discussed. Furthermore, the dependence and interdependence relationships of RIFs have not been considered in depth neither properly illustrated in these models. Since lack of understanding and limited information are the major hazards [8] and primary causes of epistemic uncertainties [26,27], there is a need to adopt appropriate modeling techniques that allow for inference in the presence of uncertainty.

To address the main challenges related to modeling risks of a ship stuck in ice during transit along Arctic waters, we combine the expert knowledge elicitation with a dataset from voyages through the NSR. This dataset includes ship performance data and associated surrounding environmental data, including wind speed, air temperature, visibility, sea temperature, ice concentration, ice thickness, wave height, ship speed and engine. The BBN can combine data obtained from various sources, which is required here, since the dataset recorded during ship transit does not cover the whole modeling space. Since the dataset is not complete, covering specific conditions only, we elicited knowledge from five experts and incorporated this into the BBN model to fill the gap.

The primary feature of the resulting risk model is that it enables to measure the effect of combinations of various input risk influencing factors (variables) on the output called risk indicator. The latter is the probability of a ship stuck in ice. Indeed, by backward propagation of the evidence in the BBN, one can determine the most probable combination of the input variables required to achieve a predefined output – the probability of a ship stuck in ice. The risk model is also validated, with the use of a framework suitable for models that are elicited from experts or which are based on scarce and limited datasets. The results of the validation show strong agreement with the state-of-the-art models available and a general understanding of the analyzed phenomena. The model provides an insight into the combined effect of risk factors on the probability of a ship stuck in ice, and it properly distinguishes between different scenarios. In principle, it can assist onshore managers or the ship's crew in planning and conducting an actual sea passage through Arctic waters.

The remaining of the paper is organized as follows. Section 2 introduces the adopted methodology. Section 3 presents risk influencing factors (RIFs), the adopted case and correspond data