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An operational risk analysis tool to analyze marine transportation in Arctic waters

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ABSTRACT

The Arctic Ocean has drawn major attention in recent years due to its rich natural resources and shorter navigational routes. Arctic development and transportation involve significant risk caused by the unique features of this region, such as ice, severe operating conditions, unpredictable climatic changes, and remoteness. Considering the high degree of uncertainty in the performance of vessel operating systems and humans, robust risk analysis and management tools are required to provide decision-support to prevent accidents and ensure safety at sea. This paper proposes an Object-Oriented Bayesian Network model to dynamically predict ship-ice collision probability based on navigational and operational system states, weather and ice conditions, and human error. The model, when integrated with potential consequences, may help estimate risk. A case study related to oil tanker navigation on the Northern Sea Route (NSR) is used to show the application of the proposed model to predict oil tanker collision with sea ice.

1. Introduction

Marine transportation is an important service sector to support natural resource development and international commerce. Safety and efficiency are two critical concerns of the marine industry. The Arctic Climate Impact Assessment report [18] states that the extent and the amount of ice in the Arctic region is decreasing. Therefore, forthcoming years may see reduced difficulty for marine transportation in Arctic waters. This may increase the potential of ship accidents in the region [9].

Navigation safety becomes a more critical issue considering various risk factors such as ice, severe operating conditions, unpredictable climatic changes, and remoteness. Also, the performance of vessel systems degrades in harsh environments, which consequently increases the risk of collision. Khan et al. [21] identified extremely low temperature, multi-year sea-ice, ice-ridges, and pack-ice as the main causes of the increasing potential of ship accidents in the Arctic regions. Marchenko et al. [25] have made similar conclusions. The authors mention that mineral exploration, fisheries, tourism, research, and naval operations are restricted due to the limited infrastructure, low temperatures, sea ice, icing, and polar lows. Human error is another main contributor to accidents [31]. Li et al. [24] summarize 87 academic research papers and project reports to analyze frequency and consequences based risk estimation models separately. They argue that human error is of utmost importance in ship navigation and recommend more research in this field. The study by Goerlandt and Montewka [15], discusses the scientific definitions and approaches related to maritime risk analysis and show that the probabilistic approach and the approaches based on realism and experiments are effective in this field.

A few recent attempts have been made to develop risk models for Arctic shipping, Sahin and Kum [32] present various navigational risk factors in the Arctic ocean, determine the numerical weights for each risk factor using a Fuzzy-AHP approach, and calculate the risks with numerical probabilistic levels. Risk matrices are used to assess frequencies and consequences of grounding, collision (with sea ice and others), fire, violence or terror for various cruise ships, cargo, tankers, petroleum installations and fishing boats in the Norwegian and the west Russian Arctic regions [25].

A quantitative risk assessment (QRA) is an effective tool to capture a broad picture of risk of accidents, as (a) in QRAs risk is usually described in terms of probabilities and expected values of hazards and, (b) it has the ability to treat uncertainties related to the risk obtained for the desired event [14]. Risk has been defined as expected value, probability of an undesirable event, uncertainty, potential losses, probability and severity of consequences, event or consequences, consequences + uncertainty, and effect of uncertainty on objectives [7,15]. Montewka et al. [27] use the QRA approach to develop a proactive

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Table 1
Risk factors and their associated OOBNs in the ship-ice collision model.

OOBNs	Risk factors
Ship Navigational System States	Effective Radio Communication
	Radar Effectiveness
	Safe Maneuverability in Ice Covered Waters.
	Use of Navigational lights and Search lights
	Ice Charts
Ship Operational System States	Effective Route Planning
	Effective Safety Measures
	Safe Operations in Ice
	Season
	Ship Class
	Speed
Weather System States	Blowing Snow
	Fog
	Long Polar Nights
	Visibility
	High Winds
	Seasons
Ice States	Ice Thickness
	Ice Types
	Ice Strength
	Pieces of Floating Ice/ Icebergs
	Drifting Ice
Human Error	Inadequate Technical Knowledge
	Inadequate Knowledge of own Ship System
	Decision based on Inadequate Information
	Inadequate Communication
	Fatigue

framework for estimating risk of maritime transportation in the Gulf of Finland. This study focuses on ship-ship collision in an open sea involving RoPax vessels. They adopt Bayesian Belief Networks (BBN) as a tool to model collision risk and quantify the uncertainties of the model. To dynamically assess the transportation risk, Khan et al. [21] propose a cause-consequence based model using Bayesian networks (BN). They estimate the probability of maritime accidents and their related consequences. Some hindrances to maritime risk assessments, such as missing data and fuzziness, are discussed in Zhang [37]. The author concludes that fuzzy logic, analytical hierarchal process (AHP), evidential reasoning (ER) and BNs are advantageous to deal with uncertainties because they can combine objective data with subjective knowledge. An approach to estimate the effect of the role of human factors in ship collision by means of BN is proposed by Hänninen and Kujala [16]. They consider data from the Gulf of Finland and discover the most plausible human factors affecting the BN. Hänninen et al. [17] link safety management to maritime traffic safety indicated by accident involvement, incidents reported by Vessel Traffic Service, and the results from Port State Control inspections. They use BN and the model parameters are based on expert elicitation and learning from historical data. An innovative approach to integrate human and organizational factors into risk analysis is presented by Trucco et al. [33]. A BN is developed to model the Maritime Transport System (MTS) by considering its different actors (ship-owner, shipyard, port and regulator) and their mutual influences. Conditional probabilities are estimated by means of experts' judgments collected from an international panel of different European countries. Finally, a sensitivity analysis is carried out to identify configurations of the MTS leading to a significant reduction of accident probability during the operation of a high-speed craft. The difficulty of risk analysis in RoPax transport is dealt by developing a BN that exploits expert surveys [36]. The results indicate that the BN model can effectively address the problem of data deficiency and mutual dependency of incidents in risk analysis. It can also model the development process of unexpected hazards and provide decision support for risk mitigation.

The above discussion indicates the usefulness of BN as an approach to model maritime risk. But some limitations with a standard BN representation make it difficult to learn, construct, update, infer and reason complex models. In this paper, we focus on key risk factors affecting safe navigation in the Arctic waters. Object Oriented Bayesian Network (OOBN) is proposed as an approach to model and analyze ship-ice collision accidents due to the following reasons:

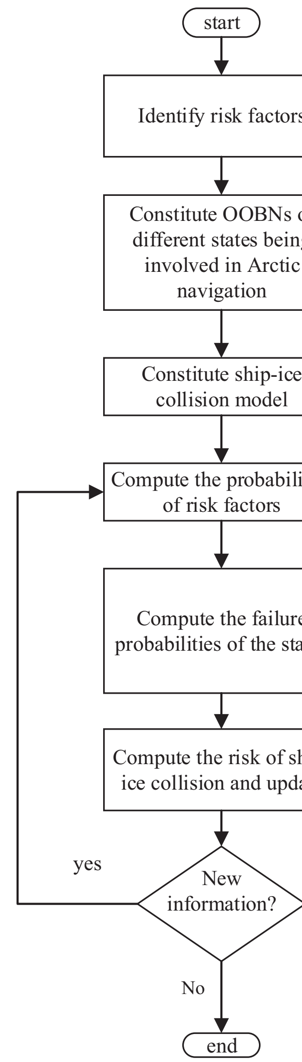

Fig. 1. General Framework of (OOBN) Framework.

(1) OOBNs are simple to construct, ready for reuse and flexible for modification,
(2) compared to standard BNs, their structure is less complex for better communication and explanation [22], and
(3) they provide a modular approach such that evolving complexity in the model is effectively represented.

This paper aims to develop a quantitative risk assessment tool using Object Oriented Bayesian Network to assess the probabilistic risk of ship-ice collision in Arctic waters. The model can be integrated with other decision support systems on corrective operational interventions. The remainder of the paper is structured as follows: Section 2 gives a brief overview of OOBNs, an OOBN based risk assessment methodology for ship-ice collision is proposed in Section 3; Section 4 presents an application of the proposed model through a case study that uses a hypothetical accident scenario related to oil tanker collision with ice along the NSR and discusses the results of a sensitivity analysis and the model's uncertainties. Section 5 concludes this study and proposes some future research directions.