Safety Science 141 (2021) 105335

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

# Review and comparison of existing risk analysis models applied within shipping in ice-covered waters

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ARTICLE INFO

*Keywords:*
Risk analysis
Ship
Ice-covered waters
Arctic
Modelling

ABSTRACT

With the changing climate and declining extent of sea ice, the activities in the Arctic region have become increasing significantly. Compared to the environments with ice-free waters, the harsh environment in the Arctic is due to ice, low temperatures, remoteness, etc., all of which will complicate ship operations. Research on the shipping risk analysis in ice-covered waters is important because such research can improve the management of shipping businesses and aid accident prevention initiatives in the Arctic. In this paper, we systematically review and compare risk models for shipping in ice-covered waters to report experiences in the field and to identify existing knowledge gaps. This work provides a broad review and comparison of the state-of-the-art risk analysis models by considering the models' purposes, theoretical frameworks, risk factors, and outputs, and it includes an analysis of the field-specific terminology that is used to define accidents. The results indicate that the risk analysis of the Arctic faces challenges, as a complete overview of accident data is not easy to find. There has been significantly less research done on convoy operations in ice and overtaking and meeting in an ice channel. In addition, interactions between risk factors and human factors are not sufficiently understood and thus need to be further studied. Being familiar with knowledge gaps acts as a catalyst for further research on risk analysis within shipping in Arctic conditions.

## 1. Introduction

Statistical data reported by the Protection of the Arctic Marine Environment Working Group show that the total distance sailed by all types of vessels increased by 75% in the Arctic from 2013 to 2019 (PAME, 2020), while harsh environmental conditions, e.g., ice, extremely low temperatures, darkness, thick ice, etc., complicated ship operations. High-latitude Arctic marine ecosystems are vulnerable, and the capability of search and rescue is low in the Arctic, which implies that the consequences of ship accidents resulting in oil spills may be very serious (Kujala et al., 2019a). One challenge related to shipping in the Arctic is how to prevent accidents from happening while an increasing number of industries are aggressively trying to maximize the opportunities offered by the receding ice edge. Although accidents cannot be eliminated, they can, however, be controlled by applying risk analysis procedures. Risk analysis is a way of identifying and assessing factors that could negatively affect the success of a project. This analysis allows one to examine the risks and helps to decide whether to move forward with a decision.

A comprehensive review of the fundamental issues related to the risk analysis of maritime transportation was carried out by (Goerlandt and Montewka, 2015), in which risk definitions, risk perspectives, and risk analysis approaches were analysed and compared. For ice-free waters, several reviews focusing on risk models have been conducted from quantitative and qualitative perspectives (Goerlandt et al., 2017b; Li et al., 2012; Ozbas, 2013), from an application area perspective (Chen et al., 2019; Huang et al., 2020; Ozturk and Cicek, 2019; Qi and Cui, 2001), from a vessel behaviour modelling perspective (Zhou et al., 2019), from a risk management process perspective (Kulkarni et al., 2020), etc. In contrast to the risk analysis of ice-free waters, the amount of research that has been conducted on the risk analysis of ice-covered waters, especially the Arctic, is considerably less. The earliest academic study (published in English) focusing on the risk analysis of ice-covered waters dates to 2005 and is a technical report discussing the risk analysis of winter navigation in the Baltic Sea (Jalonen et al., 2005). Subsequently, several conference papers (Kubat et al., 2012; Kujala et al., 2019b; Li et al., 2017; Marchenko et al., 2017) and journal papers (Abbassi et al., 2017; Goerlandt et al., 2017a; Goerlandt et al., 2017c;

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https://doi.org/10.1016/j.ssci.2021.105335
Received 26 December 2020; Received in revised form 24 March 2021; Accepted 2 May 2021

Khan et al., 2020; Khan et al., 2018; Montewka et al., 2015; Zhang et al., 2017; Zhang et al., 2019a; Fu et al., 2021) have been published and have reported different models that have been applied for risk analysis.

With the increasing interest in navigating the Arctic, legislatures are also coming to realize the significance of improving shipping safety in polar waters. To enhance the maritime safety and protection of the vulnerable environment in polar regions, the International Maritime Organization (IMO) issued an international legally binding instrument, namely, the International Code for Ships Operating in Polar Waters (Polar Code), which was developed by the IMO between 2009 and 2015 and entered into force on 1 January 2017 (IMO, 2014). In particular, referenced in the Polar Code, a methodology named the Polar Operational Limit Assessment Risk Indexing System (POLARIS) was developed to help assess operational capabilities and limitations in ice (IMO, 2016). On 20 April 2020, the Emergency Prevention, Preparedness and Response (EPPR) working group of the Arctic Council released a Guideline for Arctic Maritime Risk Assessment (GAMRA), indicating that the safety of shipping in the Arctic is also attracting the attention of this organization (EPPR, 2020).

Despite a growing number of frameworks and models for analysing shipping risks in ice-covered waters, comprehensive and systematic reviews of the existing models are lacking. To address this shortcoming, this paper provides a broad review and comparison of the existing risk analysis models by considering the models' purposes, theoretical frameworks, risk factors, and outputs. This paper also includes an analysis of the field-specific terminology that is used to define accidents. Risk analysis models for autonomous shipping and/or navigation under ice are excluded. We also summarize the modelling techniques and the advantages and disadvantages of each of the models. Suitable references are included to highlight certain features, along with diagrams and charts that are used to illustrate the differences in each approach. The results of this study provide some insights into research trends in ice-covered waters and highlight knowledge gaps.

The remainder of this paper is organized as follows. Section 2 defines the important terminology for this study. Section 3 describes methods for collecting literature and for review and comparison of models. Subsequently, Section 4 presents the results of the literature review. A discussion is provided in Section 5. Section 6 concludes the paper and puts forward some recommendations for future research directions.

## 2. Terminology and definitions

### 2.1. Risk definition

Risk analysis is the process of gathering data and synthesizing information to develop an understanding of a particular enterprise (ABS, 2000). The International Organization for Standardization (ISO) put forward a general definition of risk, which is the effect of uncertainty on objectives. To be more accurate, risk is usually expressed in terms of risk sources, potential events, their consequences and their likelihood (ISO, 2018). In maritime rules, the IMO has defined risk as the combination of the frequency and the severity of consequences (IMO, 2018). Some additional definitions of risk can be found in the literature. A review of the definitions and meanings of the nine concepts of risk was conducted by Aven (2012). From an engineering perspective, Kristiansen (2004) used risk as an objective safety criterion, and risk is normally applied as $R = P{\cdot}C$, where $P$ is the occurrence probability of an accident (e.g., a ship-ice collision), and $C$ is the consequence concerning economic, human and/or environmental loss. Kaplan (1997) proposed that three elements should be determined in regard to risk: "scenario", "likelihood", and "consequences". This definition was followed by Rausand and Haugen (2020), who defined the *risk as the combined answer to the following three questions: (1) What can go wrong? (2) What is the likelihood of that happening? and (3) What are the consequences?* This paper adopts the definition put forth by Rausand and Haugen (2020).

### 2.2. Terminology of accident

To classify the collected papers that discuss accidents that have occurred in ice-covered waters, we adopt a unified terminology of accidents from the IMO (2018) and the report by Jalonen et al. (2005), with small modifications. The reasons to define this terminology are discussed in Section 5.2. The following definitions are used:

- *Collision*: striking or being struck by another ship, regardless of whether underway, anchored, or moored. This category does not include striking underwater wrecks;
- *Ship-ice collision*: striking or being struck by ice that causes damage to ship.
- *Besetting in ice*: being surrounded so closely by ice that eventually the ship is unable to move or maneuver under its own power or steer using its steering gear;
- *Contact*: striking any fixed or floating objects (except ice) other than those included under the definitions of collision or grounding;
- *Grounding*: being aground or hitting/touching the shore or sea bottom or underwater objects (wrecks, etc.) or being aground on ice, such that external assistance or significant effort is necessary to be refloated; and
- *Foundering*: the vessel being filled with water from above and/or below the waterline and sinking.

### 2.3. Ice conditions

For navigation, ice conditions typically include ice concentration, ice type (age/thickness) and ice form (in plane dimensions). In addition, information on ice conditions may include the degree of hummocking/deformation, the ice decay stage, snow cover characteristics, ice drift, and ice compression.

### 2.4. Conditions on the route

The two terms *open water* and *ice-free waters* can easily be assumed to have the same or very similar meanings. Although both terms indicate that ships can navigate freely, they are not the same. The definitions of these two terms are as follows:

- *Open water*: a large area of freely navigable water in which sea ice is present in concentrations less than 1/10 (WMO, 2014).
- *Ice free waters*: no ice is present, if ice of any kind is present, this term shall not be used (IMO, 2014).

### 2.5. Mode of operation in ice-covered waters

Vessels can navigate through ice with assistance or in unassisted movement. The latter case is often referred to as *independent navigation*. Navigating with icebreaker assistance is common when the ice concentration, the existing ice ridges and/or the ice compression make the ship hard to operate. Fig. 1 illustrates four modes of operation with icebreaker assistance. Typically, the assisted modes of operation are decomposed into five practical operations (Goerlandt et al., 2017c; Kujala et al., 2007):

- *Escorting operation*: an icebreaker breaks an ice channel, followed by an assisted ship at a recommended distance and/or speed and/or mode of the main engine.
- *Breaking a ship loose operation*: an icebreaker breaks the ice that closely surrounds a ship, thus releasing the stuck ship from ice pressure. This operation may also be called a freeing ship operation or cutting loose.
- *Convoy operation*: this operation is similar to the escorting operation, but there are several ships following the icebreaker. The suitable distances, mode of the main engine and/or speed of the vessels in

**Fig. 1.** Different modes of operation in ice-covered waters.

| Thumbnail ID | Mode of operation | Source |
|---|---|---|
| 1 | Icebreaker Kapitan Dranitsyn escorting merchant ships to Franz Josef Land | PortNews (2016) |
| 2 | Icebreaker Rosatomflot convoying three vessels through Northern Sea Route | High North News (2018) |
| 3 | Icebreaker Kontio notch towing a general cargo vessel | Heinonen (2017) |
| 4 | Icebreaker *γmer* breaking loose a stuck ship from her quarter | Buysse (2007) |

convoy are generally decided by the icebreaker captain and depend on the ice conditions.

- *Double convoy operation*: two icebreakers are involved in breaking the ice when the assisted vessel has a larger breadth than the icebreakers. In this operation, the other icebreaker travels ahead or behind and slightly to the side of the first icebreaker.
- *Towing operation*: the icebreaker tows the assisted ship when the channel closes quickly due to ice pressure, the channel has too much brash ice, and/or the assisted ship cannot perform appropriately on ice.

## 3. Methodology

### 3.1. Literature collection

Relevant literature was systematically collected using keyword searches across multiple databases, such as Google Scholar, Engineering Village, and Web of Science. The keywords included the words “risk”, “risk analysis”, “risk assessment”, “collision”, “ship-ship collision”, “ship-ice collision”, “besetting in ice”, “stuck in ice”, “accidents”, “incidents”, “ice-covered waters”, “ice-infested waters”, “winter navigation”, “Arctic”, and “Baltic sea”. The studies included in this review were published in English between January 1990 and March 2021 and described risk analysis methods that have been applied to ice-covered areas. Publications in languages other than English were not considered in this study.

Based on the records extracted from the databases, all the titles and abstracts were thoroughly examined to further filter out the references that were not closely related to the topic. Papers that did not provide enough information about the risk analysis of marine traffic in ice-covered waters were excluded. In addition, a snowball search was conducted in two ways: (1) searching all the relevant articles in the references and (2) searching the relevant articles from all co-authors.

### 3.2. Systematic approach to risk models comparison

We analysed the collected risk models considering four distinctive but overlapping aspects: the purpose(s) of the model, the theoretical framework, the risk factors considered, and the output(s) of the model.

#### 3.2.1. Model purpose(s)

To achieve the purpose of risk analysis, five types of risk calculations (RC1-RC5) from large scale to small scale were outlined:

RC1: Average risk level for all types of ships;
RC2: Average risk level for a specific type of ship;
RC3: Risk level for one specific ship;
RC4: Risk level for one specific ship on one specific voyage; and
RC5: Risk level for one specific ship at a time point.

The analysis and comparison of the model purposes were then performed from the three following aspects:

(i) Is the model for type RC1, RC2, RC3, RC4, or RC5?
(ii) Is it a calculation for a single ship or ship(s) with icebreaker assistance?
(iii) Is it a calculation of total risk or for one specific accident type?

### 3.2.2. Theoretical framework

The theoretical frameworks applied to shipping in ice-covered waters were reviewed, including their strengths and weaknesses. For details, refer to Section 4.2.

### 3.2.3. Risk factors

The risk factors considered by the models were grouped into nine categories (see hierarchy structure in Fig. 2). Explanations of the risk factor categories are given below, and the results of the risk factor analysis are reported in Section 4.3:

- *Outside vessel organization-human* (O-O-H): human influencing factors such as incorrect route selection and unreasonable fleet decomposition in convoy operations may cause potential accidents. Human influencing factors originate from the seamen of the icebreaker, the ship company, the maritime safety administration not announcing navigational warnings in time, etc., excluding the seamen of the ship, who are taken as objects of the risk analysis.
- *Outside vessel organization management* (O-O-M): the risk factors belonging to this group may include the management of icebreaker services companies, ship companies, maritime safety administrations, etc. Examples of such risk factors may be the insufficient power of the icebreaker, the insufficient width of the icebreaker, the rules of operating in ice (e.g., different ship operators may have different rules on astern operation with conventional propellers), etc.
- *Outside vessel-environment-weather* (O-E-W): weather influencing factors refer to meteorological factors such as temperature, fog, rain, etc.
- *Outside vessel-environmental channel* (O-E-C): the channel condition refers the ice conditions, traffic flow, water depth, navigation aids, etc. in the navigational channel.
- *Inside vessel-technical-static character* (I-T-S): this refers to the ship's static technical parameters such as ship type, ship class, ship age, ship length, etc.
- *Inside vessel-technical-dynamic character* (I-T-D): this is the opposite of I-T-S, such that the dynamic factors are those related to the movement of ship and those that can change during a voyage, for example, ship speed, engineering power, ship course, etc.
- *Inside vessel-technical-equipment* (I-T-E): this refers to the failure of equipment onboard.
- *Inside vessel-organization-human* (I-O-H): seamen onboard contribute to these factors, which include, for example, a lack of situational awareness, negligence, judgement failures, unmaintained safety distance, deviation from the suggested route, etc.
- *Inside vessel organization management* (I-O-M): this type of risk factor refers to the management onboard the vessel, such as improper preparedness for the towage, communication failure, bridge team, etc.

### 3.2.4. Models' output

The four types of output that were used to compare the collected models are accident description, occurrence probability, major risk factors, and risk level. The results are reported in Section 4.4. Accident description refers to information about ice conditions, environment, modes of operation, ship type, etc. Occurrence probability refers to the chances that an identified accident could occur. Major risk factors refer to the factors that significantly influence the probability or consequence of an accident. Risk level is defined as the product of the consequence of the identified accident and its likelihood (e.g., high, moderate, and low risk level).

## 4. Results

As a result of the literature search, 29 original articles and one guideline were found that discuss the risk analysis of shipping in ice-covered water. An overview of the annual number of publications is shown in Fig. 3.

A summary of the reviewed literature is given in Appendix A, including information on the theoretical approach to risk analysis, the geographical area of application, the accident type, risk factors, the availability of an uncertainty analysis, and the input data for the model.

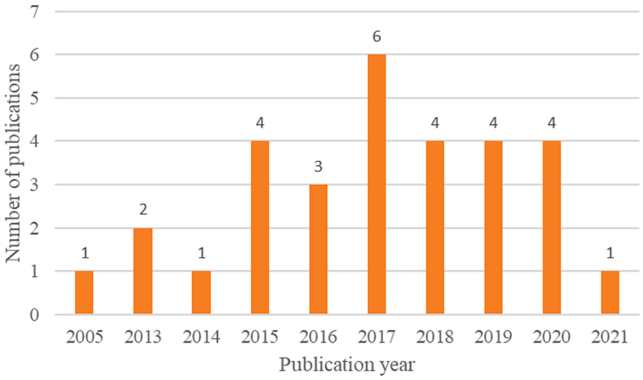

**Fig. 3.** Number of articles published per year.

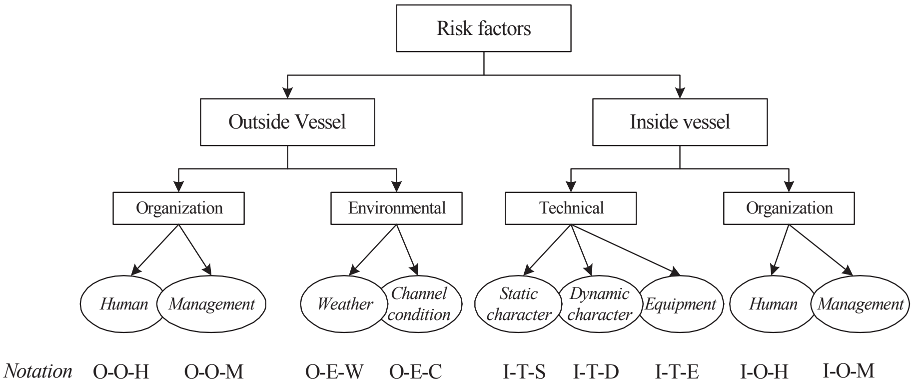

**Fig. 2.** The risk factor classification structure.

### 4.1. Model purposes

Table 1 provides an overview of the purposes, operation modes and accident types that are addressed in the identified models. The mode of operation is marked by different colours, and the accident type is described with an abbreviation.

The results in Table 1 show that 40.6% of the models focus on calculating the average risk levels for all types of ships (RC1), whereas four models address the risk calculation for a specific ship type (RC2). The second most frequent risk calculation of one specific ship on one specific voyage type (RC4) was focused on by nine models. Risk levels for one specific ship (RC3) and for one specific ship at a time point (RC5) are addressed by four and five models, respectively.

Regarding the mode of operation, nine models focus on independent navigation, six models focus on escort operation, and only one model focuses on convoy operation. Among these models, five models analyse the shipping risk related to independent navigation and escort operation, and five models analyse the shipping risk related to independent navigation and icebreaker assistance; however, the exact mode of operation with icebreakers is either not clear or contains more than two types of mode of operation. Finally, five models do not explicitly clarify their mode of operation during modelling, and the mode of operation cannot easily be determined from the context.

Regarding accident type, 14 models analyse ship-ice collisions, 12 models analyse collisions, nine models focus on ship besetting in ice, four models focus on operation limitations, six models focus on grounding, and three models analyse foundering. Four models do not define an accident type.

### 4.2. Theoretical framework

The risk analysis techniques in each model are described in this section.

### 4.2.1. POLARIS

*4.2.1.1. Description.* POLARIS has been referenced by the IMO in the Polar Code as an acceptable method for providing guidance on the operational limitations in polar waters. Many concepts of this method are carried over from the Arctic Ice Regime Shipping System (AIRSS). The major difference between POLARIS and AIRSS is that POLARIS allows for the consideration of limited speed and escort operations, as well as the effects of seasonal ice decay on ice strength. POLARIS relies on the use of an ice regime, which is defined as a description of an area with a relatively consistent distribution of any mix of ice types, including open water. The concentration of each ice type within an ice regime is reported in tenths. In POLARIS, for each ice type and ice thickness, there is an associated ice type score defined for each particular polar ship class. The ice type score is referred to as a risk value (RV), and a collection of RVs that correspond to a particular ice regime is referred to as a risk index outcome (RIO). A RIO is determined by summing the RVs for each ice type present in the ice regime encountered, multiplied by its concentration:

$$\mathrm{RIO} = \sum_{i=1}^{n} \mathrm{C_i} \times \mathrm{RIV_i} \tag{1}$$

where RIO is the risk index outcome, $\mathrm{C_i}$ represents the concentrations (in tenths) of ice types (including ice free area) within the ice regime, $\mathrm{RIV_i}$ represents the corresponding risk index values for the vessel's ice class.

(1) RIV outcome for independently navigating ship

The operational limitations for ships operating independently are determined based on the criteria in Table 2.

*Elevated operational risk*: Two suggestions are given for elevated operational risk. 1) If ships are of elevated operational risk, the ship should limit its speed in addition to providing additional watchkeeping or using icebreaker support. The recommended speed is shown in Table 3. 2) The reduction of speed should be avoided if this may impair ship manoeuvrability. These suggestions lead to a paradoxical situation; i.e., when the calculated RIO is from −10 to 0, the first suggestion recommends that the ship reduce speed in case the ship is damaged, but the second suggestion recommends not reducing speed. How to handle this situation is not clear in practice.

*Operation subject to special consideration*: The ship operators should exercise extreme caution when navigating on ice. The procedures taken to reduce the risk may include course alteration/rerouting, further reduction in speed and other special measures.

(2) RIV outcome for escorted ship

In an escort operation, the icebreaker is taken as an independent navigating ship. The escort operation should be reconsidered if the icebreaker obtains a negative RIO. However, POLARIS fails to calculate the RIO for icebreakers, as icebreakers do not carry a polar class. For escorted ships, the ice regime is the area immediately ahead of the ship, which includes the track of the icebreaker and any unmodified ice out of the maximum beam of the escorted ship when its beam is larger than the icebreaker. For voyage planning purposes, when an icebreaker escort is intended to be used, the RIO derived from non-escorted historical ice data may be assumed to be modified by adding 10 to its calculated value as recommended in (IMO, 2016).

(3) RIV for operating in an ice regime containing glacial ice

No exact value of the RIO is given when encountering glacial ice, and no explicit safe distance is stated.

*4.2.1.2. Collected literature.* Several applications of POLARIS exist in the reviewed literature. Stoddard et al. (2016) applied POLARIS to estimate RIOs along the planned route with historical ice data in the Canadian Arctic region and identify the areas where unusual kinematic behaviour of the ship may occur along the route. Kujala et al. (2019b) used POLARIS to find a suitable ship class for independently navigating in the Antarctic and navigating with an icebreaker in the Kara Sea. Bond et al. (2018) introduced the technical background of POLARIS, adopted the data from Kujala et al. (2019b) to show how to use POLARIS, and provided an enhancement of POLARIS. Browne et al. (2020) modified the calculation of RIO based on the determined operational exposure level, which is dependent on the life safety of a ship, and the environmental and socioeconomic consequence categories associated with the vessel and its planned route. The modified equation is:

$$\mathrm{RIO} = \sum_{i=1}^{n} \mathrm{C_i} \times (\mathrm{RIV_i} + \mathrm{RIV_L}) \tag{2}$$

where $\mathrm{RIV_L}$ is the RIV adjustment factor. The adjustments correspond to the operational exposure level, as shown in Table 4.

*4.2.1.3. Strengths and weaknesses.* POLARIS considers the differences in ice conditions between summer and winter seasons by adjusting the risk index values to the first-year ice type. It is easy to use for the estimation of the operational limitations for real-time operation and route planning. POLARIS considers 11 ice types, but guidance is not provided for situations when it is difficult to distinguish between first-year, second-year, and multiyear ice. The risk posed by glacial ice (ice of land origin) is not well handled (e.g., what should be a safe distance between a ship and the iceberg). By nature, POLARIS does not account for vessel type, and it only considers the ice class. Therefore, the risk index does not reflect the full risk picture with respect to the consequences of an accident. The risk indices of a general cargo vessel and an oil tanker (both

**Table 1**
Summary of models' purposes.

| Reference | RC1 | RC2 | RC3 | RC4 | RC5 |
|---|---|---|---|---|---|
| Jalonen et al. (2005) | 🟥 SIC, C, G | | | | |
| Critch et al. (2013) | ⬜ C, SIC, G | | | | |
| Kubat et al. (2013) | 🟦 BII | | | | |
| Khan et al. (2014) | | | 🟥 C or SIC | | |
| Valdez Banda et al. (2015) | ⬜ C, BII, G, SIC | | | | |
| Kum and Sahin (2015) | 🟨 C, G | | | | |
| Marchenko (2015) | | 🟩 G, SIC | | | |
| Montewka et al. (2015) | | | | 🟨 BII | |
| Fu et al. (2016) | | | | 🟦 BII | |
| Stoddard et al. (2016) | | | 🟦 * | 🟦 * | 🟦 * |
| Valdez Banda et al. (2016) | ⬜ C and SIC | | | | |
| Abbassi (2017) | | | | 🟦 SIC, G, F | |
| Afenyo et al. (2017) | 🟩 SIC | | | | |
| Goerlandt et al. (2017a) | ⬜ C, G, SIC | | | | |
| Ivanišević (2017) | | | | 🟨 ND | |
| Li et al. (2017) | | | 🟩 BII | | |
| Mussells et al. (2017) | 🟩 BII | | | | |
| Baksh et al. (2018) | | | | 🟦 SIC&C, G, F | |
| Bond et al. (2018) | | | | 🟩 * | 🟩 * |
| Fu et al. (2018) | 🟨 BII | | | | |
| Khan et al. (2018) | 🟩 SIC | | | | |
| Zhang et al. (2019a) | 🟦 C | | | | |
| Kujala et al. (2019b) | | | | | 🟨 * |
| Zhang et al. (2019b) | | | | | ⬜ ND |
| Khan et al. (2019) | | | | 🟧 C | |
| Browne et al. (2020) | | 🟩 * | | | |
| Khan et al. (2020) | | | | | 🟩 SIC |
| EPPR (2020)-ASRM | | | | ⬜ C, G | |
| EPPR (2020)-SAMSON | | 🟥 C, G, F | | | |
| EPPR (2020)-HFO | | 🟥 C, SIC, G | | | |
| Zhang et al. (2020a) | 🟩 BII, SIC | | | | |
| Vanhatalo et al. (2021) | | | 🟥 BII | | |

Modes of operation:

| | |
|---|---|
| 🟩 Independent navigation | 🟦 Escort operation |
| 🟨 Independent navigation & escort operation | ⬜ Independent navigation and icebreaker assistance |
| 🟧 Convoy operation | 🟥 Not defined |

Accident types:

C=Collision, SIC=Ship-ice collision, BII=Besetting in ice, G=Grounding, F=Foundering, ND=Not defined.

* Covers all ice-related accident types (e.g., besetting in ice, ship-ice collision).

**Table 2**
RIO criterion (IMO, 2016).

| RIO | Ship class | |
|---|---|---|
| | PC1-PC7 | Below PC7 & not assigned ship class |
| RIO≥0 | Normal operation | Normal operation |
| −10≤RIO< 0 | Elevated operational risk | Operation subject to special consideration |
| RIO<-10 | Operation subject to special consideration | Operation subject to special consideration |

**Table 3**
Recommended speed limits for elevated-risk operations (IMO, 2016).

| Ice class | Recommended speed limit |
|---|---|
| PC1 | 11 knots |
| PC2 | 8 knots |
| PC3-PC5 | 5 knots |
| Below PC5 | 3 knots |

**Table 4**
The relationship between RIV and operational exposure levels (Browne et al., 2020).

| Operational exposure level | RIV adjustment factor |
|---|---|
| L1 | $\mathrm{RIV}_{L1} = -2$ |
| L2 | $\mathrm{RIV}_{L2} = -1$ |
| L3 | $\mathrm{RIV}_{L3} = 0$ |
| L4 | $\mathrm{RIV}_{L4} = +1$ |

having the same ice class) calculated under the same ice conditions would be equal. However, in the case of an accident such as a ship hull breaking, the consequences would be much worse for an oil tanker, e.g., in regard to an oil spill; thus, the risk (probability times the consequences) would be greater for an oil tanker than for a cargo vessel. This is not reflected in risk index calculations. Another limitation of POLARIS, as noted by (Fedi et al., 2018), is that it does not explicitly consider human factors.

### 4.2.2. Bayesian networks (BNs)

*4.2.2.1. Collected literature.* Critch et al. (2013) created a BN model in an attempt to determine the factors leading to accidents such as collisions and grounding through a hazard session with maritime industry experts, discussions with Finnish icebreaker crews and a review of available literature. The authors investigated which operation a merchant vessel was performing and the hazards and hazardous events that may lead to a certain accident. This work was limited to a qualitative analysis.

Khan et al. (2014) estimated the probability of a collision in Arctic waters and analysed the consequences. The risk factors were determined by experts.

Fu et al. (2016) developed a BN model for a ship besetting in ice, and the major contributing factors were ranked through a sensitivity analysis. The risk factors were derived from the literature and expert discussion. Human factors were not considered in this paper.

Valdez Banda et al. (2016) followed the steps of a formal safety assessment and adapted these steps to a BN model to estimate the probability of a collision that leads to oil spills.

Afenyo et al. (2017) built a BN for ship-ice collisions that aimed to find the major contributing risk factors. The prior probabilities of nodes were obtained from published literature.

Li et al. (2017) built a BN to estimate the probability distribution of the states of ship speed (state 1: 3–7 knots, state 2: 7–10 knots, state 3: over 10 knots) under different ice conditions and levels of propulsion power. The lower the ship speed attained was, the higher the probability that besetment would occur was.

Similarly, Montewka et al. (2015) developed BNs to estimate the probability distribution of the states of ship speed (state 1: below 5 knots, state 2: 5–10 knots, state 3: over 10 knots) in given ice conditions and the probability of a ship besetting in ice. In this BN, the ice concentration had 3 states, while the thickness of different types of ice (level ice, ridged ice, rafted ice, etc.) had 2 states.

Baksh et al. (2018) developed a BN to investigate the probability of ship-ice collision, foundering, and grounding in Arctic waters, and the major risk factors were also analysed through sensitivity analysis.

Khan et al. (2018) constructed an object-oriented BN to analyse ship-ice collisions.

Khan et al. (2019) developed a BN integrated with the Nagel-Schrekenberg model to analyse the collision probability of a convoy operation in the Vilkitskii Strait. The Nagel-Schrekenberg model was adopted to estimate the ship density in convoy operations, which affects two factors: maintaining a safe distance between two ships and maintaining a safe speed. The different probabilities of collision under different ship densities in convoy operations were calculated.

Khan et al. (2020) developed a dynamic BN to estimate the risk of ship-ice collisions based on the hypothetical form of observation. The different states of risk factors at different timesteps contributed differently to the current risk.

Zhang et al. (2020a) developed a BN to estimate the probabilities of accident occurrence and the severities of the consequences for ships besetting in the ice and of ship-ice collisions. The sensitivity of risk factors for ship besetting in ice, ship-ice collision, composite risk (contains ship besetting in ice and ship-ice collision) is analysed, respectively. The safe speed for independent shipping in the Arctic was also recommended.

Vanhatalo et al. (2021) used a hierarchical Bayesian model to assess the probability of ship besetting in ice. Their model was based on AIS data, satellite ice data, and real-life ship besetting events data.

*4.2.2.2. Strengths and weaknesses.* BNs are flexible for building the interrelationships between variables (e.g., between ice thickness and ship speed). In addition, they consider multiple states of variables, which implies that the multiple states of ice concentration, ice types, etc. can be considered in BNs. In addition, BNs consider the interactions between risk factors by adopting conditional probability tables (CPTs). However, CPTs are mainly based on expert judgement in the collected literature, which may have limitations depending on the experience of the experts.

### 4.2.3. Statistical analysis (SA)

In marine risk analysis, statistical analysis is a method used to analyse the collected accident data, aiming to find useful information related to accidents. The data sources may include books, papers, accident databases, ship bridge blogs, etc.

*4.2.3.1. Collected literature.* Jalonen et al. (2005) calculated the frequency of accidents that occurred in the Baltic Sea based on the data developed by Hänninen (2004).

Kubat et al. (2013) collected information about ships besetting in ice from four vessels that experienced 10 besetting episodes in Frobisher Bay, and the relationships between these accidents and the salient factors were examined. These besettings occurred during escort operations; however, the effect of icebreakers was not considered in this paper.

Kum and Sahin (2015) used route cause analysis (RCA) to analyse accidents that occurred north of 66°33′ to identify the causes of different accident scenarios.

Valdez Banda et al. (2015) analysed accidents from four winter seasons in Finnish waters to identify the type of accident, type of vessel involved in the accident, the contribution of the deadweight tonnage of vessels, the sea areas where the accident occurred, and the ice conditions of the accident. The results were then compared with expert assessments to conclude that the findings from the data were reasonably similar to expert judgements.

Marchenko (2015) calculated the frequency of incidents that occurred in Svalbard waters, mainland Norway, and the Russian part of the Barents Sea in 2012 based on traffic history.

Goerlandt et al. (2017a) analysed the accident database for the Baltic Sea. A comprehensive analysis of the profile of accidents was performed, including accidents in relation to sea ice conditions, precipitation, visibility and temperature, and wind and collision accidents in relation to convoy and escort operations, cut loose operations, and independent navigation.

Afenyo et al. (2017) collected accident data from ArcticData (http://arcticdata.is/) and the literature to identify the most significant causal factors of ship iceberg collisions.

Mussells et al. (2017) collected 33 records of ships besetting in ice in the Hudson Strait from ship bridge logs during 2005–2014. With the collected data, the ice pressure and ridge densities when besetting occurred were analysed.

Zhang et al. (2019a) proposed an improved Human Factors Analysis and Classification System (HFACS) to identify the risk factors that contribute to ship collision between ship and icebreaker, by collecting various accident databases (including the Swedish Accident Investigation Board, Marine Accident Investigation Branch, FleetMon).

The Guideline for the Arctic Marine Risk Assessment has introduced several methods for conducting risk assessment. A common feature of these methods is that they employ statistical analysis to analyse the frequency of accidents in the region they focus on (EPPR, 2020).

*4.2.3.2. Strengths and weaknesses.* One strength of statistical methods is that they can provide fundamental and comprehensive information related to the accident, such as what causes the accident and the corresponding accidents. This fundamental information helps researchers understand some differences in accidents between ice-covered waters and ice-free waters. However, these methods are unlikely to provide a complete understanding of these differences due to limited data and experience. In the Arctic, especially in the Russian Arctic, the amount of available accident information is limited. Furthermore, accident underreporting is more pronounced in the Arctic. For example, the Marine Accident Investigation Branch (MAIB) identified four collisions and contacts made between 1993 and 2011 (Kum and Sahin, 2015); however, according to the Arctic Marine Shipping Assessment (AMSA) report, 22 collisions occurred in the Arctic from 1995 to 2004 (Ellis and Brigham, 2009).

### 4.2.4. *Fault tree analysis*

*4.2.4.1. Collected literature.* Kum and Sahin (2015) developed different fault trees (FTs) for collision and grounding in Arctic waters. The risk factors were derived from accident data from 1993 to 2011 through root cause analysis (RCA), and the probability of each basic event was determined by several experts.

Abbassi et al. (2017) developed FTs for accident collisions, grounding and foundering and an event tree (ET) for collisions. However, the consequences of collisions were not quantified.

Zhang et al. (2019a) conducted a fault tree analysis for collision accidents in an escort operation by considering risk factors derived from accident reports and expert judgements.

*4.2.4.2. Strengths and weaknesses.* FTA can integrate expert knowledge and historical accident data during the modelling procedure. In the collected papers, the FTs were developed based on logical reasoning. This method can easily describe the combinations of events and conditions that lead to the accident (top event). However, due to the nature of the binary state of events, it is unachievable in this process to describe the factors containing multiple states. For example, in a grounding fault tree, "bad weather conditions" cause "uncontrollable factors" (Kum and Sahin, 2015). "Bad weather conditions" may be classified into a number of states that have a different probability of leading to "uncontrollable factors". In the fault tree analysis, only two states (weather conditions causing uncontrollable factors and weather conditions not causing uncontrollable factors) can be modelled.

### 4.2.5. *Others*

*4.2.5.1. Risk state assessment method.* Zhang et al. (2019b) combined approaches (projection pursuit method, mapping function, information diffusion theory) to conduct real-time risk state and risk prediction. Fifteen risk indices were determined in advance, and relative data were collected every half hour. The projection pursuit method was applied to reduce the dimensionality of the collected raw data. The raw data were projected to a one-dimensional plane along the best projection direction, which was obtained with predetermined risk grading criteria. The mapping function was used to transform the one-dimensional risk information into corresponding risk grading levels. After this, risk diffusion was applied to obtain the risk probability distribution to depict the risk state. The output was in the form of probability distributions of different risk levels (four risk grading levels from 1 to 4) in this study.

*4.2.5.1.1. Strengths and weaknesses.* The method's outcome is a risk probability distribution rather than a single probability value. This method does not use expert judgments to estimate the risk probability distribution. To some degree, it eliminates the qualitative effect from expert judgment. A disadvantage of this approach is that it could be difficult to distinguish between different risk levels when the risk probability distribution is close to uniform.

*4.2.5.2. Exsecpert Assessment.* Valdez Banda et al. (2015) organized three meetings with interview experts to ask questions about hazardous scenarios that may occur, their corresponding accidents, and their causes in shipping both with and without icebreaker assistance. The experts included two icebreaker captains, two vessel traffic service operators, and one pilot. By comparing the evaluations made by the experts with an analysis of accident data from four winters (2002–2003, 2009–2012), some of the results made by experts were confirmed by the statistical analysis, while the difference in results indicates that some uncertainties exist in the risk analysis of shipping in ice-covered waters.

*4.2.5.2.1. Strengths and weaknesses.* Expert assessment can supplement the knowledge that is revealed from accident data, and it can also be used to confirm the results of statistical analysis, e.g., ship-independent navigation is the most complex navigation in Finnish sea areas. However, the accuracy of expert assessment largely depends on the experience of shipping. A suitable number of experts and sufficient experience with shipping need to be considered to carry out an expert assessment.

*4.2.5.3. Risk Matrix.* Jalonen et al. (2005) and Marchenko (2015) used a risk matrix to define the level of risk by considering the category of probability or likelihood against the category of consequence severity. As a qualitative method, the occurrence of accidents and consequences were described by linguistics.

*4.2.5.3.1. Strengths and weaknesses.* This method makes it easier for those who are not experts to understand the risk associated with shipping in ice coverage. However, the output is qualitative.

*4.2.5.4. HAZID and HAZOP.* HAZID means hazard identification. Ivanišević et al. (2017) used this method to analyse the shipping risk and consequences related to the Ob River and Kara Sea when operating at low temperatures, the onboard working and living conditions at low temperatures and operating under different ice conditions.

*4.2.5.4.1. Strengths and weaknesses.* This modelling technique presents only the average consequence.

*4.2.5.5. Event Tree Analysis (ETA).* Fu et al. (2018a,b) developed a fuzzy event tree to analyse accident scenarios of ships besetting in ice, in which nine intermediate events and five outcome consequences were identified.

*4.2.5.5.1. Strengths and weaknesses.* ETA can present various consequences, but the probability of each consequence is mainly estimated by experts for Arctic conditions.

### 4.3. Risk factors taken into consideration

Accident data analysis and expert consultations are the two main resources used to determine the risk factors for marine traffic. Based on expert knowledge, Sahin and Kum (2015) listed 79 risk factors for maritime navigation in the Arctic region. The 79 risk factors were grouped into 7 categories, i.e., 1) risk factors outside the vessel, 2) risk factors related to structural design and arrangement of equipment locations, 3) risk factors related to technical faults in vessel equipment, 4) issues related to the operation and placement of equipment onboard, 5) risks related to cargo, fuel and related handling equipment, 6) communicational, organizational, operational instruction faults and routine failures, and 7) human factors, interpretation, awareness & assessment of the situation. Fu et al. (2018a) adopted a hierarchical model for the identification of the critical risk factors (RFs) of the Arctic maritime transportation system. Humans, ships, the environment, and management were used to group 32 risk factors. Zhang et al. (2019a) analysed accidents during escort operations and identified risk factors from the perspective of human error. Fundamental ship-icebreaker collision risk factors were identified from the statistical analysis of accident reports and expert judgement. The classification was performed by using the Human Factors Analysis and Classification System (HFACS), which includes unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational factors. Using the same method, the factors contributing to ship-ice collisions were also identified (Zhang et al., 2020b).

Det Norske Veritas (DNV) was engaged by the IMO to plan, perform and report on a hazard identification workshop to identify the factors of shipping in polar waters (Nigam and Fowler, 2011). GAMRA also highlighted the risk factors for shipping in the Arctic.

The results of the risk factors considered in different accident scenarios are illustrated in a Sankey diagram (see Fig. 4). The detailed information on risk factors in each paper corresponds to the last column in Appendix A.

In collisions, the highlighted risk factors are communication failures between the icebreaker and the escorted ship; high speeds and short distances; icebreaker operation failure or other ship faults; and a lack of situational awareness.

In ship-ice collision analysis, the dominant factors are environmental factors, including wind, waves, fog, snow, ice conditions, and technical and human factors on board. The subservient factors are human and organizational factors outside the vessel and the static features of the vessel.

For ships besetting in ice, there are two main research directions. The first direction is to estimate the ship's performance in various ice conditions, which means that a ship besetting in ice is mainly dependent on ice thickness and ship speed. The other direction is causal analysis, in which the environmental factors and the ship's static features are also taken into consideration. However, human factors are not considered in the current study.

In grounding, the weights of factors are almost the same. However, a ship's static features, such as ship type and class, and a ship's dynamic features, such as ship speed, are not taken into consideration. Ships' static features, such as ship class and ship structure, are the dominant factors in foundering.

### 4.4. Output of risk models

Table 5 presents the outputs of the risk analysis models based on the classifications mentioned in Section 3.2.4.

## 5. Discussion

In this section, a discussion is provided based on the results presented in Section 4. This discussion is centred around the identified knowledge gaps and accident terminology.

### 5.1. The knowledge gaps found in the review

#### 5.1.1. Interactions among risk factors

Interaction effects among risk factors mean that a risk factor will have a different effect on its causative event, depending on the status of another risk factor (Aven et al., 2006). Not considering interactions among risk factors in risk analysis may lead to erroneous results (Guo et al., 2018). It is reasonable to believe that ice's impact on ship operation is related to environmental risk factors, such as wind, waves, bathymetry, etc., and that human performance during ship operation is also related to both environmental and organizational factors. For example, complex ice conditions may cause fatigue of an operator due to maintaining vigilance for a long time. In most of the collected papers, the risk factors were assumed to be independent. Risk analysis models,

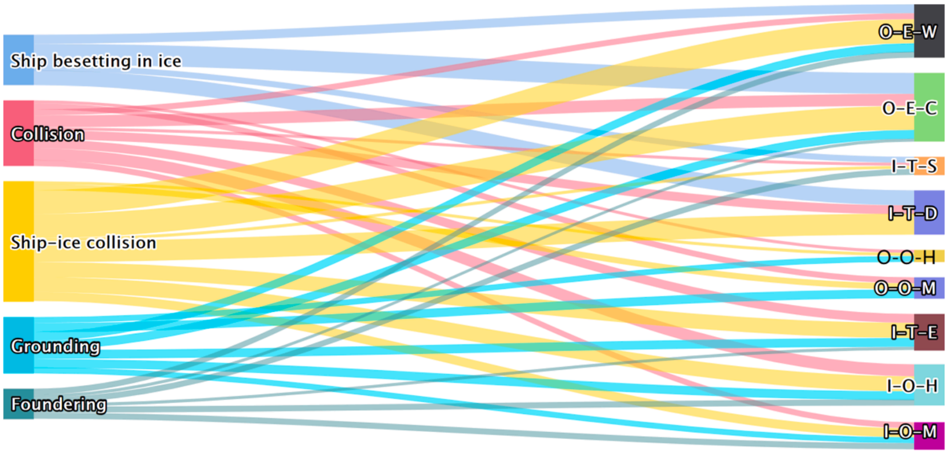

**Fig. 4.** Sankey diagram of risk factors considered in different accident scenarios.

**Table 5**
Summary of the outputs of the risk models.

| References | Modelling techniques | Accident description | Probability | Major RFs | Risk level |
|---|---|---|---|---|---|
| Stoddard et al. (2016)<br>Bond et al. (2018)<br>Kujala et al. (2019b)<br>Browne et al. (2020) | POLARIS | | × | | |
| Critch et al. (2013) | | | | × | |
| Baksh et al. (2018) | | | × | × | |
| Khan et al. (2014) | | | × | | × |
| Fu et al. (2016) | | | × | × | |
| Afenyo et al. (2017) | | | | × | |
| Khan et al. (2018) | BN | | × | × | |
| Li et al. (2017) | | | × | | |
| Montewka et al. (2015) | | | × | | |
| Valdez Banda et al. (2016) | | | × | | |
| Khan et al. (2019) | | | × | × | |
| Khan et al. (2020) | | | × | × | |
| Zhang et al. (2020a) | | | × | × | × |
| Vanhatalo et al. (2021) | | | × | × | |
| Kum and Sahin (2015) | | | × | | |
| Abbassi et al. (2017) | FT | | × | | |
| Zhang et al. (2019a) | | | × | | |
| Kubat et al. (2013) | | × | | × | |
| Valdez Banda et al. (2015) | | × | | | |
| Marchenko (2015) | | | × | | |
| Afenyo et al. (2017) | SA | | | × | |
| Goerlandt et al. (2017a) | | × | | | |
| Mussells et al. (2017) | | × | | | |
| Zhang et al. (2019a) | | | | × | |
| EPPR (2020) | | | × | | |
| Zhang et al. (2019b) | RSA | | × | × | |
| Jalonen et al. (2005)<br>Marchenko (2015) | Risk Matrix | | | | × |
| Ivanišević et al. (2017) | HAZID & HAZOP | | | × | |
| Fu et al. (2018a,b) | ET | | × | | |

Note that the majority of the reviewed models do not address the consequences of the accident and rather focus on the probability of occurrence and/or the major risk factors.

such as BNs, can consider the interactions among risk factors by using conditional probability tables. However, it is a challenge to quantify the interaction among risk factors from a fundamental viewpoint. To date, the probability tables for Arctic conditions have only been determined through expert judgements and are thus limited by the operational experience of experts. Research on interactions among risk factors in Arctic conditions may start from environmental risk factors. Environmental factors (low temperatures, wind, waves, visibility, polar darkness) affect technical and human factors. Low temperatures and rain/snow can lead to an icing effect on ship equipment, e.g., affect the rotation of the radar antenna, thereby causing a malfunction of the radar. Polar darkness might have an effect on human performance and affect the detection of ice conditions in front of the ship. Harsh weather conditions (e.g., high waves) as well as complex ice conditions might also affect human performance. Interactions among environmental factors also exist. Except for fog, rain and snow will also affect visibility.

### 5.1.2. Risk factors in Polar Code (Introduction, part 3) and literature

In the Polar Code (IMO, 2014), ten risk factors that may lead to elevated levels of risk are identified. It is of interest to compare these factors with the factors considered in the reviewed literature. Table 6 lists the number of reviewed models that consider each Polar Code risk factor and is followed by a description of the knowledge gaps found.

The results of the risk factors comparison indicate some knowledge gaps:

(1) Some Polar Code risk factors (such as topside icing, remoteness, lack of emergency response equipment, and environment) are rarely taken into consideration in the reviewed models. The extended daylight factor has not been considered in the models.
(2) Polar Code points out that human performance is affected by ice, low temperature, extended periods of darkness or daylight. However, knowledge on what and how human performance is affected by these risk factors in the Arctic conditions is limited in the considered literature.
(3) The reviewed models frequently consider parameters related to the ship (i.e., ships ice class, speed, etc.). However, these parameters are not explicitly considered as risk factors in Polar Code.

### 5.1.3. The human factors in ships besetting in ice

The risk factors considered in different accidents are reviewed in Section 4.3. An obvious finding is that human factors were not considered in accidents related to ships besetting in ice. Previous research has shown that human factors are the main contributing factors to maritime accidents (Akyuz, 2017; Akyuz and Celik, 2015). In the Polar Code, human factors such as the training of the crew are also highlighted (IMO, 2014). Two salient crew performances, i.e., factors that can largely determine the probability of a ship besetting in ice, are as follows: 1) visually checking the ship's progress by looking over the side of the vessel instead of trusting the speed log or the GPS output due to delay when the ship's speed drops below 3–4 knots and 2) keeping the rudder amidships so as not to lose power when the ship's speed is reducing (Buysse, 2007). This implies that the experience of the ship's crew and good seamanship are important in this situation. However, this is not

**Table 6**
Risk factors in Polar Code and the reviewed literature.

| Risk factor in Polar Code | Number of models considering this risk factor |
|---|---|
| Ice | 31 |
| Topside icing | 1 |
| Low temperature | 7 |
| Extended periods of darkness or daylight | Darkness (1), extended daylight (0) |
| High latitude | 11 |
| Remoteness | 2 |
| Lack of crew experience | 4 |
| Lack of emergency response equipment | 1 |
| Severe weather conditions | 18 |
| Environment | 1 |

considered in the models. Another challenge is how to quantify the human factors, as details underlying ships besetting in ice events are rarely (if at all) published.

#### 5.1.4. Lack of available accident data from the Arctic

SA is important, e.g., for revealing the causes of accidents occurring in the Arctic (Kum and Sahin, 2015) and in the Baltic Sea (Goerlandt et al., 2017a), for identifying the causes of collisions in an escort operation (Zhang et al., 2019a), and for calculating the frequencies of accidents (Jalonen et al., 2005). Further analysis of accident databases might provide valuable insights into the mechanism of accidents that have occurred in the Arctic (Kujala et al., 2019a). However, statistics on accidents that have occurred in the Arctic are difficult to find. There have been several attempts to compile accidents in the Arctic and provide related statistics (see a summary of the available data in Table 7). These data resources are not detailed enough, i.e., they do not provide enough information on the sequence of events causing the accidents (Kujala et al., 2019a), which makes statistical analysis less useful in risk assessment.

#### 5.1.5. Lacking models to assess risks during overtaking or meeting situations in a narrow ice channel

The accidents and modes of operation are summarized in Section 4.1. An obvious finding is that collision accidents are not studied for independent navigation. Knowledge related to the risk analysis of overtaking and meeting situations in a narrow ice channel is lacking. The scenarios related to overtaking and meeting situations are illustrated in Fig. 5 (Buysse, 2007). During an overtaking/meeting situation, Step 3 may lead to a great risk of collision if the bow of ship is scraping along the track's side or the ship bounces back, especially in the meeting situation. The safe relative speed between the two vessels and the safe minimum distance (D1 in Fig. 5) need to be further studied.

#### 5.1.6. Convoy operations in the Arctic

Convoy operation has been taken as the best and most efficient way of facilitating vessel navigation in the Baltic Sea (Asplund, 2011). With the increasing shipping activities in the Arctic, it is no surprise that this operation will be more common in the future. In a normal pattern, the weakest vessel is the first vessel to be behind the icebreaker, followed by the strongest ship in the line, while the third vessel is of mid-level weakness. However, on some occasions, it could be better to have the stronger and wider vessel just behind the icebreaker, creating a wider channel for the weaker and smaller vessels. The cargo of the vessels must also be considered when forming the convoy. The current research (only one model) considered three risk factors: the distance between two ships, safe speed in ice, and safe operation in ice (Khan et al., 2019). In practice, other risk factors may largely contribute to collisions in convoy operations. These additional factors are summarized as follows:

**Table 7**
Summary of accident data resources in the Arctic (Kujala et al., 2019a).

| Ref. | Time | Region | Data Source |
|---|---|---|---|
| Kubat and Timco (2003) | 1978–2002 | Canadian Arctic | CHC/IRS database |
| Kum and Sahin (2015) | 1993–2011 | North 66°33′, | MAIB |
| Marchenko (2012) | 1900–1990 s | Russian Arctic | Not stated |
| Ellis and Brigham (2009) | 1995–2004 | Arctic | * |
| Hill (2010) | late 1800 s – late 1900 s | Canadian Arctic | Ship iceberg collision database |

* Lloyd's Marine Intelligence Unit Sea Searcher Database, Canadian Transportation Safety Board (Marine), Canadian Hydraulics Centre- Arctic Ice Regime System Database.

1. Ship's characteristics. Prior to the formation of the convoy, the master of the icebreaker will require relevant details of the vessels, including the length of the vessel, beam, the turning radius of the vessel, the loaded tonnage and cargo type, the sailing draft, the horsepower and the effective maximum speed. This information will help the master designate the position of each participating vessel. The length of the assisted vessels may also affect the route selection by the icebreaker when the convoy makes a turn. The icebreaker needs to ensure that the turn angle of the ice channel is wide enough for the longest ship to turn effectively in the channel.
2. Communication between ships. The convoy operation is executed under the order of the convoy commander (the master of the icebreaker), and the participating ships are expected to pass all communication through him. Quantitative analysis of communications by Zhang et al. (2020c) shows that there is a link between the communications and the distances between the ships and their speed. Therefore, timely and effective communication in convoy operations plays a great role, especially when an emergency occurs.
3. Environmental factors: Environmental factors include wind, waves, visibility, etc. Among them, visibility will largely affect the watch of ship operators, which increases the collision risk when ahead of ship stops or decelerates.
4. Human watch: Vigilance by watch officers for irregular movement, including stopping or astern motions of ahead vessels, should be continuous. This requires the watch officer to be concentrated and respond immediately once irregular movement occurs.

#### 5.1.7. State of the ice channel created by icebreaker

The icebreaker is used to facilitate navigation in ice-covered waters for assisted ships by opening an ice channel. The ice channels may have different characteristics, e.g., ice channels filled with brash ice or ice channels that are ice free, as shown in Fig. 6. The risk index outcome, according to POLARIS, should be modified by adding 10 to the risk index outcome, which is derived from non-escorted historical ice data. This is a simple way of expressing that the ice conditions in an ice channel are better than the ice conditions met with by the ship navigating independently. However, other reviewed models do not clearly describe how to treat the ice conditions in the ice channel (e.g., thermal state of the brash ice). It is necessary to conduct more research on the ice conditions in a channel, e.g., how to describe the "ice conditions" in an ice channel (an old channel vs a new channel), how fast a created ice channel closes, etc. (note that the traffic density may also affect the conditions in the ice channel).

### 5.2. The necessity to clarify the terminology

#### 5.2.1. The current terminology of hazardous events used in ice-covered waters

A unified terminology of maritime accidents in ice-covered waters provides a direct and effective way to improve the understanding of maritime risk. When describing the accidents/incidents that occurred in ice-covered waters, the terminology varies from paper to paper and from database to database.

To illustrate this variance, we refer to the terminologies used by three databases: DAMA (Kujala et al., 2009), MAIB (Kum and Sahin, 2015), and AMSA (Ellis and Brigham, 2009). The DAMA database consists of marine casualty reports given to the Finnish Maritime Administration (FMA) and accident registrations acquired from the Baltic Marine Environment Protection Commission HELCOM (Helsinki Commission) (Kujala et al., 2009), which covers the accidents that occurred in the Gulf of Finland. The Marine Accidents and Investigation Branch (MAIB) investigates marine accidents involving UK vessels worldwide and all vessels in UK territorial waters (Kum and Sahin, 2015). The

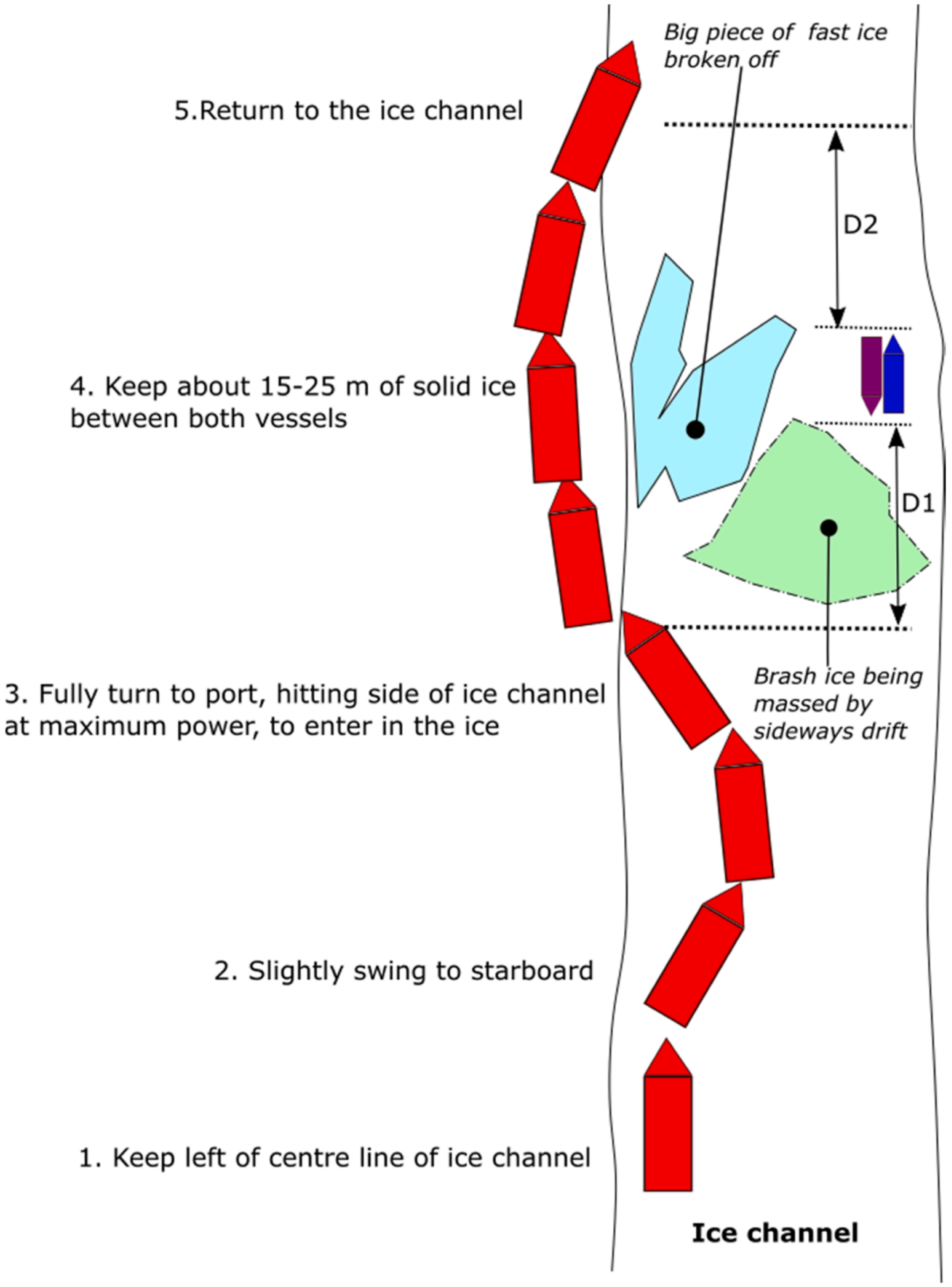

**Fig. 5.** Overtaking and meeting in an ice channel (Buysse, 2007).

**Fig. 6.** Ice channels created by an icebreaker. (a) Brash ice channel (Credit: US Coast Guard) (b) Open-water ice channel (Credit: Aker Arctic).

AMSA database covers the Arctic region and is obtained from the Arctic Marine Shipping Assessment 2009 Report (Ellis and Brigham, 2009).

Each database adopts different terminology, which is summarized in Table 8 (see column "terminology"). To describe a collision between ships, the terms "ship-ship collision", "collisions and contacts", and "collision" are employed in DAMA, MAIB, and AMSA, respectively. In MAIB, the term "collisions and contacts" is used to describe a collision between a ship and a floating object, including ice. In DAMA, a ship colliding with ice is termed a "collision with a floating object", while the term "damage to vessel" is used for a ship colliding with ice. In AMSA, the term "collision" is used for the collision between ships, and the term "damage to vessel" is used to define damage to the vessel that occurred due to a variety of reasons ranging from contact with the pier, collision with ice, extreme weather or other factors.

Scientific literature also adopts different terminology. It is the most difficult is to distinguish between a ship-ship collision and a ship-ice collision. The term "collision" is used for ship-ice collisions in (Abbassi et al., 2017; Critch et al., 2013) and for ship-ship collisions in (Goerlandt et al., 2017c; Jalonen et al., 2005; Valdez Banda et al., 2015). The same term is used in (Baksh et al., 2018; Khan et al., 2014; Marchenko, 2015) to refer to ship-ship collisions and ship-ice collisions without distinguishing any differences. The term "ship-iceberg collision" is used in (Afenyo et al., 2017; Khan et al., 2018) to clearly show that the research focuses on the collision between ships and icebergs.

### 5.2.2. *Clarifications of the accident*

An important finding of current terminology applications in ice-covered waters is that a commonly agreed definition of ice-related hazardous events is lacking. This lack may lead to confusion in future analyses (i.e., comparison of data in different databases, etc.)

First, not clarifying the hazardous event may affect the risk analysis process. Risk analysis requires that a clear terminology be used. If the accident records do not provide enough information to describe each accident, it will make it very difficult to use the data.

Second, the main risk factors contributing to different accidental events are not the same, which can be suggested by comparing the results in Section 4.3 and Fig. 4. For instance, communication with icebreakers and other vessel operation failures are salient factors in collisions, while they are rarely considered in ship-ice collisions.

Third, different stakeholders have different commitments to risk analysis. For example, the maritime safety authority may pay much attention to the risk level in their responsible sea areas or when estimating the operation limitation of ships proceeding in ice-covered waters. The ownership company may focus on shipping safety related to ship damage in the voyage. Therefore, clarity about the accident type is of great importance for communicating about risk and the corresponding decision making.

## 5.3. *Climate-change induced challenges*

With respect to the safety of shipping in the Arctic, the challenges caused by climate change (UN, 2009) may embody the following:

**Table 8**
Terminologies of accidents in the DAMA, MAIB, and AMSA databases.

| Database | Terminology |
|---|---|
| DAMA | Ship-ship collisions, Collisions with a floating object, Collisions with a bridge or quay, Groundings, Machinery damages, Fire and explosions. |
| MAIB | Collisions and contacts, Grounding, Machinery failure, Accident to person, Flooding and foundering, Fires and explosions, Capsizing and listing. |
| AMSA | Collision, Damage to vessel, Machinery damage/failure, Grounded, Fire/explosion. |

DAMA – Database for Marine Accidents (used by the Finnish Maritime Administration).
MAIB – Marine Accident Investigation Branch.
AMSA – Arctic Marine Shipping Assessment.

(1) Less sea ice resulting from rising temperature will increase shipping in the Arctic and could lead to opening of new shipping routes. This will put additional workload on vessel traffic services (located onshore) as well as on the planning of voyages along the little explored shipping routes.
(2) Extreme weather is becoming increasingly common, and this may cause serious accidents, such as ship-ice collisions and ship collisions. To accurately predict extreme weather events in the Arctic will be paramount.
(3) Risk-based and mission-based ship design methods (i.e., translating estimated risk values into design parameters) have been attracting attention (Soares et al., 2009). For risk-based design of an ice-going ship, the necessary knowledge includes accurate prediction of ice conditions, understanding of ship-ice interaction mechanism and hull response, etc. (Kujala et al., 2019a). Accurate predictions of ice conditions along the route are difficult. This may be one of the biggest challenges for application of risk-based ship design methods in the Arctic in view of climate change.

## 6. Conclusions

We have systematically reviewed and compared risk analysis models applied within shipping in ice-covered waters to summarize the experience in the field and to identify existing knowledge gaps. The review and comparison have been conducted considering the models' purpose (s), theoretical approaches, risk factors, and outputs, including an analysis of the terminology that is used to describe accidents. The main findings are summarized as follows:

- The four most frequently used modelling techniques are Bayesian networks, statistical analysis, POLARIS, and fault tree analysis. Bayesian networks have obtained high popularity due to their flexibility to consider different risk factors, as well as multiple states of the factors. Statistical analysis is an effective approach to estimating the frequency of accidents, and it is well incorporated into other approaches (e.g., fault trees and Bayesian networks). However, this approach heavily relies on the quality and quantity of accident databases. POLARIS is easy to use for the assessment of operational limitations, as it explicitly considers ice concentration, ice type (and decay), icebreaker assistance, ship class, and ship speed. However, other factors, such as the experience of the captain, ice compression, and the presence of ice ridges and icebergs, which may affect the safety of operations, are not taken into consideration. Fault tree analysis has been used to reconstruct accidents, but the nature of the binary state of events affects the use of this modelling technique in Arctic conditions.
- The most frequent risk factors considered in all reviewed accidents are environmental factors, in which the ice thickness, ice concentration, and ice ridges are frequently considered, whereas the ice floe size and ice age are considered to a lesser extent. The ship static characteristics are the least considered in the reviewed papers but are the most frequent risk factors found in the Guideline for Arctic Marine Risk Assessment. Interactions among risk factors are seldom considered. Finally, no model considers human factors in ships besetting in ice.
- Access to accident data in the Arctic is limited. Furthermore, a commonly accepted definition to describe ice-related accidents is lacking. The term collision may refer to collisions between ships or collisions between a ship and ice in different accident databases and papers, thus making it difficult to compare data. A unified terminology of accidents is defined in Section 2.2 that could provide a reference for future research.

- Risk analysis models for ships overtaking and meeting in ice channels, towing operations, and breaking-a-ship-loose operations are lacking. Risk analysis of escort and convoy operations in the Arctic needs further research, especially for enhancing the knowledge related to the conditions of the ice channel.

Possible future research should focus on predicting the real-time probability of ships besetting in ice by taking into account human, technical, organizational, and environmental factors; on analysis of the sequence events in an escort operation; and on predicting the probability of different consequences; Additionally, future research may focus on accident database improvement, as well as on reviewing literature written in other languages.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This work is a part of the NTNU Oceans Pilot Project-Risk, Reliability and Ice Data in Arctic Marine Environment. The authors would like to thank the reviewers for their valuable input to this paper and the first author wishes to thank Tiantian Zhu, Xue Yang, Mingyang Zhang for the valuable discussions in connection with risk modelling techniques.

## Appendix A. . Overview of risk analysis models within ice-covered waters.

| Reference | Modelling techniques | Geographical area | Accident type | Mode of operation | Uncertainty analysis | Data source | Risk factors considered in risk calculation |
|---|---|---|---|---|---|---|---|
| Jalonen et al. (2005) | SA, RM | BS | SIC, C, G | ND | N | EJ, AD | O-O-H: route planning; O-E-W: temperature, wind, visibility; O-E-C: ice thickness, ice strength, ridges, restrictions to navigation, icebreaker assistance; I-T-S: ship size, ship type and cargo, ship design, ice class; I-T-D: speed; I-O-H: experience, cautiousness. |
| Critch et al. (2013) | BN | BS | C, SIC, G | IN, EO, CN, T, CL | N | EJ | **C:** O-E-C: icebreaker slows significantly, other vessel is too close, vessel in convoy becomes stuck, vessel unable to give way.<br>**SIC:**<br>O-E-C: ice, passing vessel travelling opposite direction, passing other vessel, compressive ice, drifting ice.<br>**G:**<br>O-E-C: shallow water; I-H-O: vessel searching for the easiest route. |
| Kubat et al. (2013) | SA, IDM | CA | BII | EO | N | AD | O-E-W: wind direction; O-E-C: ice coverage and thickness, ridge sail height, ice pressure, distance to the coastline; I-T-D: ship speed. |
| Khan et al. (2014) | BN | NSR | C or SIC | ND | N | EJ | O-E-W: fog, high wind, wave, environmental obstacles; O-E-C: pack ice, ridge ice and iceberg, fault of other vessels, ice-breaker failure; I-T-D: high speed; I-T-E: equipment error, radar failure, equipment error, non-detected multi-year ice; I-O-H: human error. |
| Valdez Banda et al. (2015) | SA, EA | The Finnish maritime area | C, BII, G, SIC | IN, IS | N | HD, EJ | O-E-W: weather condition; O-E-C: ice condition;<br>I-O-M: winter navigation experience |
| Kum and Sahin (2015) | SA(RCA), FT | Arctic Region | C, G | IN, EO | N | AD, EJ | **Collision:**<br>O-O-H: improper route selection, O-O-M: external communication vessel to IB, incorrect towage operation, improper salvage operation of IB during ice breaking/cutting; O-E-C: manoeuvre failures of icebreaker, wrong directions of icebreaker, directly impact of other ships; I-T-E: steering gear failure, engine failure, anti-collision system failure, communication equipment failure; I-O-H: lack of situational awareness, deviation from suggested route, communication failure bridge team, internal communication bridge team; I-O-M: communication failure vessel to icebreaker or tugboat, improper preparedness for the towage, failures during other assistance work.<br>**Grounding:**<br>O-O-H: improper voyage plan; O-O-M: lack of external communication, insufficient number of tugboat/icebreaker, insufficient power of the icebreaker; O-E-W: bad weather conditions, environmental restrictions; O-E-C: inadequate depth, stuck by ice floe, ice floes stuck on the bottom, trend of the ship is towards the shallowness, the ship is close to the shallowness, ice drifting; I-T-E: interpretation failures of equipment, bow thruster failure, machinery failure, GPS failure, echo sounder failure, inactivated ECDIS shallowness alert; I-O-H: inadequate preventive action, interpretation failures of officers, lack of internal communication, deviation from suggested course, improper evasive manoeuvre. |
| Montewka et al. (2015) | BN | BS | BII | IN, EO | Y | HD, EJ | O-E-C: level ice thickness, level lice concentration, ridged ice concentration, ridged ice concentration, rafted ice thickness, rafted ice concentration; O-E-W: wind speed, direction of wind; I-T-D: ship speed. |
|  | SA, RM | AA | G, SIC | IN | N | EJ |  |

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| Reference | Modelling techniques | Geographical area | Accident type | Mode of operation | Uncertainty analysis | Data source | Risk factors considered in risk calculation |
|---|---|---|---|---|---|---|---|
| Marchenko (2015) | | | | | | | O-E-C: the geographical remoteness, sea ice, electronic communication challenges, lack of precise maps or hydrographic and meteorological data; I-O-M: the lack of preparedness system for emergency |
| Fu et al. (2016) | BN | NSR | BII | EO | N | EJ, LR | O-E-W: air temperature, wind speed, visitembility, sea temperature, wave height; O-E-C: ice concentration, ice thickness; I-T-D: engine power, ship speed. |
| Stoddard et al. (2016) | POLARIS | CA | * | EO | Y | HD | O-E-C: ice conditions; I-T-S: ship class. |
| Valdez Banda et al. (2016) | FSA, BN | The Gulf of Finland | C, SIC | IN, CN, T, CL | N | LR | O-E-C: ice conditions; I-O-H: human error. |
| Abbassi et al. (2017) | FT | NSR | SIC, G, F | EO | Y | EJ, HD | **Ship-ice collision:**<br>O-E-W: environmental obstacles, fog, high wind, wave; O-E-C: pack ice, ridge ice and iceberg; I-T-D: high speed; I-T-E: non-detected multi-layer ice, equipment error, radar failure; I-O-H: human error.<br>**Grounding:**<br>O-O-M: assistance does not arrive; O-E-W: environmental constraints, high wind, wave; O-E-C: pack ice; I-T-E: radar failure, loss of power, basic failure of the propeller, contaminated fuel in banker tanks, on-board fuel clean-up system fails, engine fails to operate, mechanical failure, equipment error; I-O-H: human error, human failure; I-O-M: assistance not requested.<br>**Foundering:**<br>O-E-W: heavy weather; I-T-S: faulty design, structural failure, metal failure; I-O-H: human error, not tight enough; I-O-M: excessive wear, inadequate pumping, communication. |
| Afenyo et al. (2017) | BN | NSR | SIC | IN | N | LR | O-E-W: poor visibility, snowstorms, strong winds; O-E-C: high iceberg density, predicted trajectory of iceberg; I-T-D: high ship speed; I-T-E: electronic failure of navigational equipment, mechanical failure of equipment, steering course failure, failure of propulsion, mechanical failure, software malfunction, iceberg size measurement error, position estimate error; I-O-H: human error (unfamiliar with equipment); I-O-M: human error(lapse), human error (miscommunication). |
| Goerlandt et al. (2017a) | SA | BS | C, G, SIC | IN, EO, CN, CL | N | AD | O-E-W: wind, rain, temperature; O-E-C: ice conditions; I-T-D: ship speed. |
| Ivanišević et al. (2017) | HAZID & HAZOP | Ob, KS | ND | IN, EO | N | EJ | O-E-W: low temperature, polar night; O-E-C: insufficient number of search rescue coordination centres, various ice thickness; I-T-E: equipment icing, not correct detection of ice condition, insufficient nautical charts and hydrographic data; I-O-H: crew fatigue; I-O-M: insufficient crew training. |
| Li et al. (2017) | BN | BS | BII | IN | Y | EJ | O-E-C: ice conditions; I-T-S: ship parameters; I-T-D: propulsion setting, manoeuvring state. |
| Fu et al. (2018b) | ET | Arctic | BII | IN, EO | N | EJ | O-E-C: depth of fairway, moving ice, icebreaker; I-T-S: ship engineer power. |
| Mussells et al. (2017) | SA | CA | BII | IN | N | AD | O-E-C: ridge densities |
| Baksh et al. (2018) | BN | NSR | SIC, G, F | EO | N | EJ, HD | **Ship-ice collision:**<br>O-O-H: inappropriate route selection; O-E-W: wind speed, wave height;<br>O-E-C: pack ice effect, ice-breakers failure, ridge ice and iceberg, fault of other vessels; I-T-E: non-detected multi-layer ice, navigator malfunction, digital chart error, procedure failure, radar failure, basic failure of the propeller; I-O-H: human error, human factor failure; I-O-M: map location not updated.<br>**Grounding:**<br>O-O-H: inappropriate route selection; O-O-M: insufficient tugboat use; O-E-W: wind speed, wave height O-E-C: pack ice effect, ice-breakers failure, faulty tugboat maneuver; I-T-E: navigator malfunction, digital chart error, radar failure, basic failure of the propeller, mechanical failure, operational failure, back-up power failure, power failure, engine fails to operate; I-O-H: human factor failure; I-O-M: map location not updated, procedure failure.<br>**Foundering:**<br>O-E-W: wind speed, wave height; O-E-C: pack ice effect, ridge ice and iceberg; I-T-S: faulty design, metal failure, structural failure; I-T-E: non-detected multi-layer ice, navigator malfunction; I-O-H: human error, human factor failure; I-O-M: inadequate pumping, cargo shift failure, not tight enough, excessive wear, communication failure. |

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| Reference | Modelling techniques | Geographical area | Accident type | Mode of operation | Uncertainty analysis | Data source | Risk factors considered in risk calculation |
|---|---|---|---|---|---|---|---|
| Bond et al. (2018) | POLARIS | A | * | IN | N | – | O-E-C: ice conditions; I-T-S: ship class. |
| Khan et al. (2018) | BN | NSR | SIC | IN | Y | EJ | O-O-M: radio communication; O-E-W: blowing snow, fog, long polar nights, visibility, high winds; O-E-C: use of navigational lights and search lights, ice thickness, ice types, ice strength, pieces of floating, ice/icebergs, drifting ice; I-T-S: ship class; I-T-D: speed; I-T-E: radar effectiveness, safe manoeuvrability in ice covered waters, ice charts, effective safety measures, safe operations in ice season; I-O-M: inadequate technical knowledge, inadequate knowledge of own ship system, decision based on inadequate information, inadequate communication, fatigue. |
| Khan et al. (2019) | BN, NaSch | VS | C | CN | N | – | O-E-C: channel density; I-T-D: Maximum speed, safe distance between 2 ships; I-O-H: safe operation in ice. |
| Kujala et al. (2019b) | POLARIS | BS, KS | * | IN, EO | N | – | O-E-C: ice conditions; I-T-S: ship class. |
| Zhang et al. (2019a) | HFACS, FT, SA | – | C | EO | Y | AD, EJ | O-O-H: improper route selection, lack of icebreaking ability; O-O-M: poor communication between ships; O-E-W: bad visibility, snow or rain weather; O-E-C: maneuver failures of the icebreaker, ice conditions, ice ridge, wrong course of icebreaker; I-T-D: over safety speed; I-T-E: maneuver failures of the assisted ship, engine failure, steering gear failure, anti-collision system failure, communication equipment failure, lack of engine power, anti-collision rule gap; I-O-H: lack of situational awareness, negligence, judgement failures, unmaintained safety distance, deviation from suggested route; I-O-M: lack of emergency operation. |
| Zhang et al. (2019b) | PPR, IE | NSR | ND | IN, CN | N | | O-E-W: weather conditions, air temperature, visibility level, wind level of surface, sea-surface temperature; O-E-C: ice condition level, rescue density, convoy navigation; I-T-S: ship type, deadweight tonnage, ship age, draft, operation power, ice class; I-O-M: staff behaviour code, continuous manual working hours. |
| Browne et al. (2020) | POLARIS | AA | * | IN | N | – | O-E-C: ice conditions, ecological sensitivity, life safety consequence; O-T-S: ship type, ship class. |
| Khan et al. (2020) | BN | BtS | SIC | IN | Y | LR | O-E-W: low temperature, fog, darkness, poor visibility, blowing snow; O-E-C: ice drift, ice concentration, type of ice, ice strength, ice-breakers failure, ridge ice and iceberg, fault of other vessels; I-T-D: speed. |
| Zhang et al. (2020a) | BN, RM | NSR | BII, SIC | IN | N | AD, EJ, LR | O-E-C: ice concentration, ice thickness; O-T-D: ship speed; O-E-W: wind speed, wave height, wind wave effect |
| Vanhatalo et al. (2021) | BN, SA | NSR | BII | ND | N | AD, HD | O-E-C: ice concentration; O-T-S: ship class |

Modelling techniques: BN = Bayesian network, BA = Bayesian approach, FT = fault tree, SA = statistical analysis, IDM = ice dynamic model, FSA = formal safety assessment, RM = risk matrix, HAZID = hazard identification study method, HAZOP = hazard and operability study method, RCA = route cause analysis, HFACS = Human Factors Analysis and Classification System, POLARIS = Polar Operational Limit Assessment Risk Indexing System, EA = expert assessment, NaSch = Nagel-Schrekenberg model, PPR = projection pursuit regression, IE = information entropy.

Geography: NSR = Northern Sea Route, CA = Canadian Arctic, BS = Baltic Sea, Ob = Ob river, KS = Kara Sea, AA = Atlantic Arctic, BtS = Barent sea, VS = Vilkitskii Strait, A = Antarctic.

Accident: C = collision, SIC = ship-ice collision, BII = besetting in ice, G = grounding, F = foundering, ND = not defined.

Operation: IN = independent navigation, EO = escort operation, CN = convoy, T = towing, CL = cut loose, ND = not defined, IS = icebreaker service (exact mode of operation is not clarified).

Data: EJ = expert judgement, AD = accident data, LR = literature review, HD = historical data.

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