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Research paper

A Bayesian network model for estimating the combined risk in Northeast Passage escort operations

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ABSTRACT

Escort and convoy operations are commonly employed and highly effective strategies in the Arctic, particularly when ship navigating independently becomes challenging due to adverse ice conditions. Nonetheless, these operations are also among the riskiest, given their potential to lead to collisions between ships and icebreakers, as well as ships besetting in ice. Consequently, a robust estimation of the combined risk involved in escort/convoy systems is of paramount importance. To this end, this paper introduces a Bayesian network model to address the combined risk in escort operations, which considers both ship besetting risk and ship-to-icebreaker collision (STIC) risk factors in a unified framework. This model considers technical, environmental, human, and organizational risk factors. The model's practical applicability is demonstrated through an analysis of a genuine voyage along the Northeast Passage in August 2015. Additionally, a comparison of model outputs with captains' judgments across 14 crafted scenarios has been performed. The proposed model suggests that the main factor causing ship besetting in ice is the ice concentration, while the distance between the icebreaker and the ship is the critical factor affecting STIC risk. According to experts, visibility outweighs both the ice channel radius and navigation experience in terms of STIC risk in escort operations.

1. Introduction

The Arctic is warming faster than the rest of the world, which is leading to a reduction in the expanse of ice cover and fostering heightened maritime navigation. Data from the Arctic Council Working Group on the Protection of the Arctic Marine Environment (PAME) show that the number of unique ships in the Arctic increased by over 25% between 2013 and 2019 (PAME, 2020). However, independent navigation in the Arctic remains a challenge, particularly during the winter season and in specific areas, e.g., the East Siberian Sea during the summer season. Harsh environmental conditions, such as low visibility and unpredictable changes in ice conditions, as well as the lack of navigation aids and insufficient experience in Arctic navigation, all contribute to a challenging operational environment (Kujala et al., 2019; Li et al., 2021; Shu et al., 2023). When merchant ships experience severe ice conditions, navigating with the assistance of an icebreaker is a common and the most effective method to facilitate shipping in the Arctic (Franck and Holm Roos, 2013). Although icebreaker assistance reduces the likelihood of accidents, such as ship–ice collisions and rudder and propeller damage (in comparison with independent navigation), a ship-to-icebreaker collision (STIC) is more likely because of ships close proximity (Xu and Kim, 2023; Franck and Holm Roos, 2013; Petersburg et al., 2006; Zhang et al., 2020) and the escorted ship besetting in ice (Xu et al., 2022b), as well as a ship-to-ship collision (STSC). The STIC, indicating that the assisted ship colliding with the icebreaker, is often a result of the icebreaker significantly reducing its speed or coming to a stop, and/or the assisted ship increasing its speed while navigating in the ice channel. STSC describes situations where an assisted ship collides with another assisted ship during convoy operations. Icebreaker-to-ship collision (ITSC) refers to incidents where the icebreaker collides with the assisted ship during the operation to free the ship from ice. These accidents can result in serious consequences due to difficulties in search and rescue operations, as well as due to the vulnerability of the Arctic ecosystem. Consequently, significant efforts are required to prevent marine accidents and ensure safe shipping in the Arctic.

During escort/convoy operations along the Northeast passage, the icebreaker leads the voyage by continuously giving the assisted ship(s) orders such as distance kept from ship ahead, speed, or the engine telegraph. The modes of operation under icebreaker assistance can generally be divided into three categories: escort operations, convoy

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operations, and towing operations, as depicted in Fig. 1 (Goerlandt et al., 2017; Kujala et al., 2007; Xu et al., 2021; Kujala et al., 2019; Zhang et al., 2020).

During escort operations, the ship masters are required to maintain the specified escort distance and/or speed behind the icebreaker to the best of the ship's abilities. The distance comprises two components: the minimum escort distance and the maximum escort distance. The minimum distance is determined by the icebreaker's Commanding Officer based on the distance needed for the escorted ships to come to a complete stop after reversing to full astern from normal full-ahead speed. It is the responsibility of the escorted vessel to maintain this distance. If the ship is unable to do so and falls back, the escorted ships' captain should inform the icebreaker immediately to prevent besetment and thus resulting delays. The maximum distance between the icebreaker and the ship is determined based on the severity of the ice conditions, the distance at which the ice channel will remain open (or nearly so), and the escorted ship characteristics. Increasing the distance increases the probability of besetment, requiring the icebreaker to perform a breaking-loose operation (Canadian Coast Guard, 2012). Decreasing this distance increases the probability of collision with the leading icebreaker (or the ship ahead).

Both events, the ship besetting in ice and ship-to-icebreaker collision (STIC), could lead to serious consequences. STIC can result in ship structural damage and environmental pollution and can jeopardize the safety of the crew (Lensu and Goerlandt, 2019). A ship besetting in ice is vulnerable to grounding and hull damage due to the impact of ice, wind, waves, and currents. Additionally, besetment can cause significant disruptions to a vessel's transit schedule (Turnbull et al., 2019) and increase the probability of getting struck by an icebreaker (hereafter called ITSC) during the breaking loose operation. Past research on the risk and safety of shipping during escort/convoy operations is reviewed and summarized in the following paragraphs.

- Ship besetting in ice

To determine the most significant factors contributing to ship besetment in ice, Kubat and Sudom (2008) conducted a survey among ship captains operating in Canadian waters and analyzed the results. The survey was followed by an examination of two separate ship besetment events in the Gulf of St. Lawrence during March 2005, which revealed that ridge height and ice pressure were the primary contributing factors (Kubat et al., 2012, 2013, 2015, 2016). Additionally, 33 besetment events experienced by the MV Arctic in the Hudson Strait between 2005 and 2014 were analyzed to establish a relationship between besetment events and ridge densities (Mussells et al., 2017). Similarly, Turnbull et al. (2019) conducted an investigation of two ice besetting events endured by the vessel Umiak I in the Labrador Sea during 2012 and 2013, and six risk factors, including ice concentration, ice thickness, ice floe size, distance from the nearest coastline, wind (wind speed and direction), and current, were analyzed. Zhang et al. (2020) developed a Bayesian network (BN) to analyze ships besetting in ice and ship-ice collisions for ships navigating independently in the Arctic, and the results of the sensitivity analysis showed that the impact of five risk factors on ship besetting in ice could be classified into three levels: high impact (ice thickness), moderate impact (ice concentration and ship speed), and less impact (wind and wave). This research focuses on independent navigation. Nevertheless, the existing body of research concerning ships besetting in ice during escort/convoy operations remains limited (Xu et al., 2021). Xu et al. (2022b) developed a BN model to predict the probability of ships besetting in ice along the Northern Sea Route during convoy operations, and the study found that ice concentration was the most significant factor, followed by the state of the ice channel and navigation experience. Montewka et al. (2015) developed two BNs to predict a ship's performance in an ice field, analyzing the joint effect of ice conditions on a ship's speed and the probability of a ship besetting in ice during a mix of independent navigation and escort operations. The concentration and thickness of different types of ice and ice compression were considered in the models. Vanhatalo et al. (2021) used a hierarchical Bayesian approach to calculate the probability of besetting events based on 58 collected events and found that the ice class and higher ice concentration greatly contributed to ship besetment, while the sea area had little impact. The modes of operation of these besetting events were not specified. Fu et al. (2018) developed a Frank copula-based fuzzy event tree to quantitatively analyze the possible consequences of ships besetting in ice.

- STIC

The research direction focusing on STIC involves the collection and analysis of collision cases. Franck and Holm Roos (2013) compiled ten collision cases that occurred during escort/convoy operations in the Baltic Sea from 1985 to 2012 and identified the root causes of each collision. Zhang et al. (2019a) conducted a comprehensive study in which they collected 17 collision cases that occurred in the Baltic Sea (16 cases) and the Arctic (1 case) between 1989 and 2017. The causative factors of these collisions were then classified using the Human Factors Analysis and Classification System. To further analyze collisions between an icebreaker and an assisted ship, a fault tree (FT) model was developed in Zhang et al. (2019a). Valdez Banda et al. (2015) analyzed accident data collected from four winter periods in the Baltic Sea and found that collisions were the most common type of accident and that ice thickness between 0.15 and 0.4 m was the primary contributing factor to collisions.

- Safety distance in escort/convoy operation

In the context of escort/convoy operations, the safe distance between an icebreaker and an assisted ship has been the focus of research. Zhang et al. (2017) calculated the safe distance based on the ship-following theory, considering the acceptable ship collision frequency, ice conditions, and ship characteristics, including length, ice class, and speed. Furthermore, Zhang et al. (2018) developed a ship-following model to simulate the behavior of ships in ice conditions, taking into account the safety distance, safe speed, ice conditions, and the ship's ability to

Fig. 1. Navigation modes under icebreaker assistance: 1) Escort operation (PortNews, 2016); 2) Convoy operation (High North News, 2018); 3) Towing operation (Heinonen and Immonen, 2017).

navigate through the icy region. The model was further enhanced by considering the impact of internship communication (Zhang et al., 2019b, 2020). Khan et al. (2019) developed a BN that integrated the Nagel-Schrekenberg model to analyze the probability of collisions during convoy operations. The Nagel-Schrekenberg model was employed to estimate the ship density in convoy operations, which influences the ability to maintain a safe distance and speed between ships. Liu et al. (2022) conducted a statistical examination of the distance between ships during 239 icebreaker assistance operations (159 escort operations and 80 convoy operations) in the Baltic Sea, which were identified using an automatic identification system.

Additionally, the importance of the safe distance between ships has been emphasized in various guidelines, which are summarized in Table 1.

Earlier works focus solely on a single accident scenario, mainly on the potential for besetting in ice or on the potential for STIC. However, during a voyage, the icebreaker master and the captains of the escorted ships should identify and implement optimal risk reduction strategies, often finding a compromise between the besetting in ice and collision probabilities. From this integrated risk assessment perspective, existing models are deficient when estimating the combined risk during escort/convoy operations. This represents a knowledge gap.

This paper aims to address this gap by introducing a Bayesian network model that considers both ship besetting risk and STIC risk factors in a unified framework. Our main contributions and original features are summarized as follows.

- A new Bayesian network model that combines the risk of ship besetting in ice with the risk of STIC in a unified framework is proposed.
- A demonstration of the model's applicability for a westbound Northeast Passage of a ship (FS Ice Class 1A) in August 2015 is presented.
- An analysis involving a comparative assessment between the model outcomes and the evaluations provided by experts is conducted across a set of 14 devised scenarios.
- Recommendations for optimal distance selection for situations where visibility is deteriorating during escort operations, considering both ship besetting risk and STIC risk, are presented.

The structure of this paper is organized as follows. Section 2 presents the adopted risk definition and methodology used to estimate the combined risk during escort/convoy operations. Section 3 and Section 4 describe the model construction process followed by case studies (i.e., model application to a real voyage and a comparison of model outputs with expert judgments across 14 designed scenarios). Section 5 presents the model's validity study, model application and limitations, as well as future work. Section 6 concludes this paper.

Table 1
Summary of the descriptions of the safe distance between an icebreaker and a ship in escort/convoy operations.

Guideline/book	Description of distance	Area	Ref.
Ice Navigation in Canadian Waters	• The minimum escort distance: the minimum distance is determined on the basis of the distance needed by the escorted ship(s) to come to a complete stop, after reversing to full astern from normal full ahead speed. • The maximum distance is determined on the basis of the ice conditions and the distance at which the track will remain open or nearly so.	Canadian Arctic	Canadian Coast Guard (2012)
Polar Ship Operations	• The minimum distance is the distance within which the escorted ships can come to a complete stop. • The maximum distance is a function of the ice conditions and the length of time that the track astern of the icebreaker or escorted ship(s) will remain open.	Arctic	Sinder (2018)
Handling Ships in Ice: A Practical Guide to Handling Class 1A And 1AS Ships	• In light ice conditions, the distance should be kept between 3 and 5 cables (555 m–926 m). • In moderate ice conditions, the distance should be kept between 2.5 and 3 cables (463 m–555 m). • In severe ice conditions, the distance is reduced to 1–1.5 cables (185 m–278 m), or even 5–10 m.	Baltic Sea	Buysse (2007)

2. Definitions and methodologies

2.1. Risk

Risk is perceived and described differently by individuals, organizations, and regulations. This paper adopts the risk definition provided by Rausand and Haugen (2020), who defined 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?

- What can go wrong in an escort operation?

In an escort operation, the icebreaker takes the lead by breaking the ice and creates an ice channel for the assisted ship to follow. However, the icebreaker could stop or reduce its speed substantially due to severe ice conditions and/or limited visibility. The assisted ship could also increase its speed in the ice channel. These scenarios present the potential for a collision between the ship and the icebreaker if the space between them is insufficient for the ship to come to a halt. Furthermore, the ice channel created by the icebreaker could close (or partially close) if ice along the track is under pressure, and the assisted ship could deviate from the ice channel, resulting in the assisted ship besetting in ice.

- What is the likelihood of that happening?

The response to this inquiry is frequently conveyed in either a qualitative manner or quantitatively as probabilities or frequencies. In this paper, we used the BN to estimate the occurrence probability of ships besetting in ice and ships colliding with the icebreaker in the ice channel.

- What are the consequences?

In this paper, we only consider the damage of ship hulls in STIC and ITSC. Please note that the term STIC is used to define the scenario of a ship colliding with an icebreaker in an ice channel, while the term ITSC defines a case when the icebreaker collides with the beset ship during a breaking loose operation. The consequences are categorized into ship hull deformation and penetration, with further information available in

Section 3.4.

2.2. Ice channel

The term "ice channel" is used throughout this study to describe a pathway through ice, irrespective of the ice concentration value. When the ice concentration is high (for example, greater than 7/10), an icebreaker will break the ice, creating an ice channel. At lower concentrations, the icebreaker might simply push the ice aside rather than breaking it, leaving a path or wake in its aftermath. In this study, we use the term 'ice channel' irrespective whether it is an actual channel, a trace, or a wake behind the icebreaker.

2.3. Bayesian network

2.3.1. Theory

Bayesian networks (BNs), also referred to as Bayesian belief networks, are a class of graphical models that encapsulate probabilistic relationships among a set of random variables. The underlying theory of BNs is founded upon Bayes' theorem, as presented in Equation (1). These models are commonly utilized to perform conditional probability inference between multiple variables.

$$p(A|B) = \frac{p(B|A)p(A)}{p(B)} \tag{1}$$

where A and B are events, p(A) and p(B) are the independent probabilities of A and B, p(A|B) refers to the probability of A given that B is true, and p(B|A) represents the probability of B given that A is true. Equation (1) comprises the prior probability, conditional probability, and posterior probability of events. The prior probability refers to the likelihood of an event occurring, derived from historical data or expert opinions that are subjective in nature. The conditional probability represents the probability of event B occurring, given that event A has taken place, under the assumption that event B is a nonzero probability event. Last, the posterior probability reflects the revised probability of an event transpiring, taking into account both prior and conditional probabilities. For more details, refer to (Jensen and Nielsen, 2007; Langseth and Portinale, 2007).

2.3.2. The elements of a BN

A BN consists of three fundamental components:

- Element 1 - Nodes, which symbolize the variables;
- Element 2 - Directed arcs or lines with arrows, which depict the causal relationships between nodes;
- Element 3 - Conditional Probability Tables (CPTs), which house the conditional probability of each state of the nodes and serve to quantify the causal relationship.

2.4. Consequences

The collisions include ITSC and STIC and may result in damage to the structure of the ship and the icebreaker, oil spills, and even fatalities. According to accident statistics, oil spills and fatalities rarely occur (Jalonen et al., 2005; Franck and Holm Roos, 2013). Therefore, this paper considers only structural damage. The severity of the structural damage is classified by ship hull penetration and ship hull deformation, which are primarily influenced by the speed of the striking icebreaker/ship during the collision, the angle of collision, and the tonnage of the striking icebreaker/ship (Valdez Banda et al., 2016). The consequence matrix (see, Fig. 2) recommended by Valdez Banda et al. (2016) was readopted for the consequence estimation for ITSC (see Section 3.4.1) and SITC (see Section 3.4.2) in escort operations.

3. Model development

The combined risk associated with escort operations encompasses two primary components: the risk of a ship besetting in ice and the risk of STIC. Each of these risks is characterized by its corresponding occurrence probability and consequences. The unified BN model used to

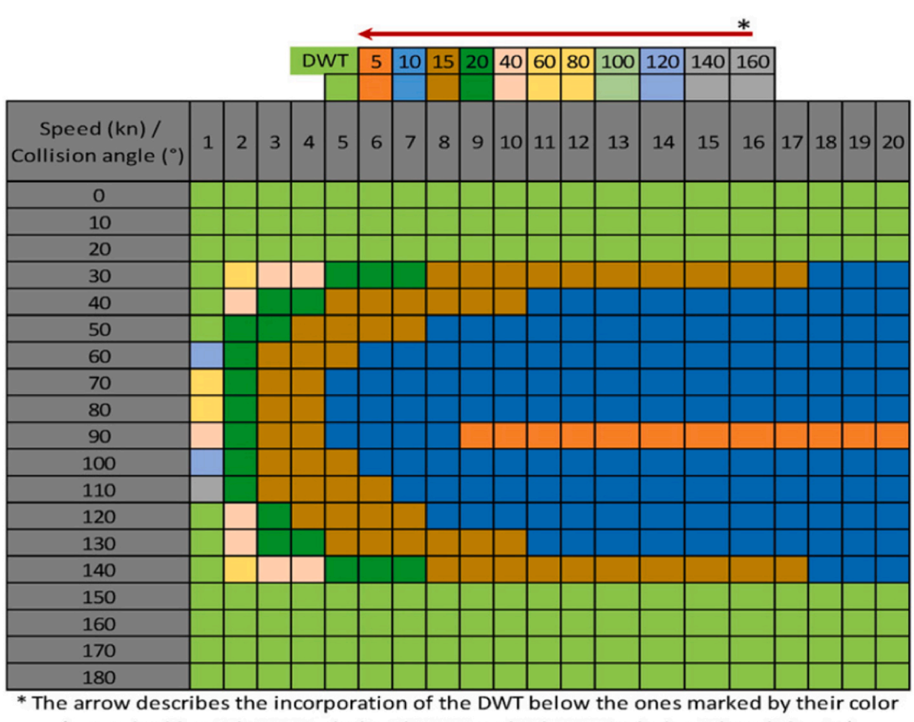

Fig. 2. Matrix describing the angle of collision and the speed of the striking vessel (classified by deadweight tonnage (DWT)), which may cause the penetration of a cargo tank in a single hull tanker in ice channel/unbroken ice (Valdez Banda et al., 2016).

estimate the probability of besetment and STIC was created by combining the developed BN besetment model (Xu et al., 2022b) with the BN STIC model transferred from the previously developed hybrid causal logic (HCL) model (Xu and Kim, 2023). The combination was facilitated by the presence of common intermediate nodes shared by both models, e.g., "conditions in the ice channel" and "ice compression".

In Section 3.1, we provide a concise introduction to the BN besetment model, while Section 3.2 details the process of transferring the STIC model. Section 3.3 explains the combination of both models.

The flowchart of the development of the combined model is illustrated in Fig. 3, the final unified BN model is shown in Fig. 4, and the definitions of the variables are shown in Appendix A.

3.1. BN model to estimate the probability of besetment

In our previous research on ships besetting in ice, a BN model was developed considering four scenarios: ship deviation from the ice channel, closure of the ice channel, failure of the engine and steering system both on the icebreaker and the ship (Xu et al., 2022b). The probabilities of failure of the engine and steering system are extremely low (e.g., 2.6×10^{-4} in Kum and Sahin (2015)). To simplify the BN model for integration with the collision model, in this study, the besetment model considers only the following scenarios:

- Ship deviation from the ice channel (i.e., the node "ship position with respect to the ice channel" in the model)
- Closure of the ice channel (i.e., the node "conditions in the ice channel" in the model)

3.1.1. Ship position with respect to the ice channel

This variable is affected by the radius of the ice channel, lookout (ship), ship maneuverability, and collision risk. An insufficient radius of the ice channel may result in the ship deviating from the ice channel because the ship enhances the power to make a turn following the ice channel. The ship may deviate from the ice channel due to insufficient lookout. The ship's maneuverability also affects the ship's ability to stay in the ice channel, such as keeping one certain course. When the crew of the escort ship perceives an elevated risk of collision due to factors such as decreasing distance, decreasing icebreaker speed, or increasing ship speed, they may decide to maneuver the ship away from the ice channel. This action, intended to avoid collision, can inadvertently result in the ship besetting in ice. The ship's lookout is affected by ship radar, crew fitness, and visibility. Crew fitness is further analyzed by crew pressure, crew fatigue, navigation experience, and level of training (descriptions of the terms can be found in Appendix, see Table 1). The ship's maneuverability is affected by ship length, loading conditions, ship speed, and officer's command. The risk of STIC estimated by ship captain is affected by the relative speed and distance between the icebreaker and ship.

3.1.2. Conditions in the ice channel (closed or partially closed)

The conditions in the ice channel are affected by icebreaker breadth (Buysse, 2007), distance between the icebreaker and ship, and ice compression. A broader icebreaker increases the likelihood of the ice channel remaining open. Additionally, a reduced distance between the icebreaker and the ship also enhances the chances of maintaining an open channel. Furthermore, a lower level of ice compression contributes to a higher probability of the ice channel remaining open. Ice compression is evaluated by the wind effect, current effect, and ice conditions.

3.2. Transfer of the HCL STIC model to the BN model

3.2.1. Occurrence probability

Our prior research developed an HCL model (Xu and Kim, 2023) including an event sequence diagram (ESD), fault tree (FT), and Bayesian network (BN) to estimate the probability of STIC in the ice

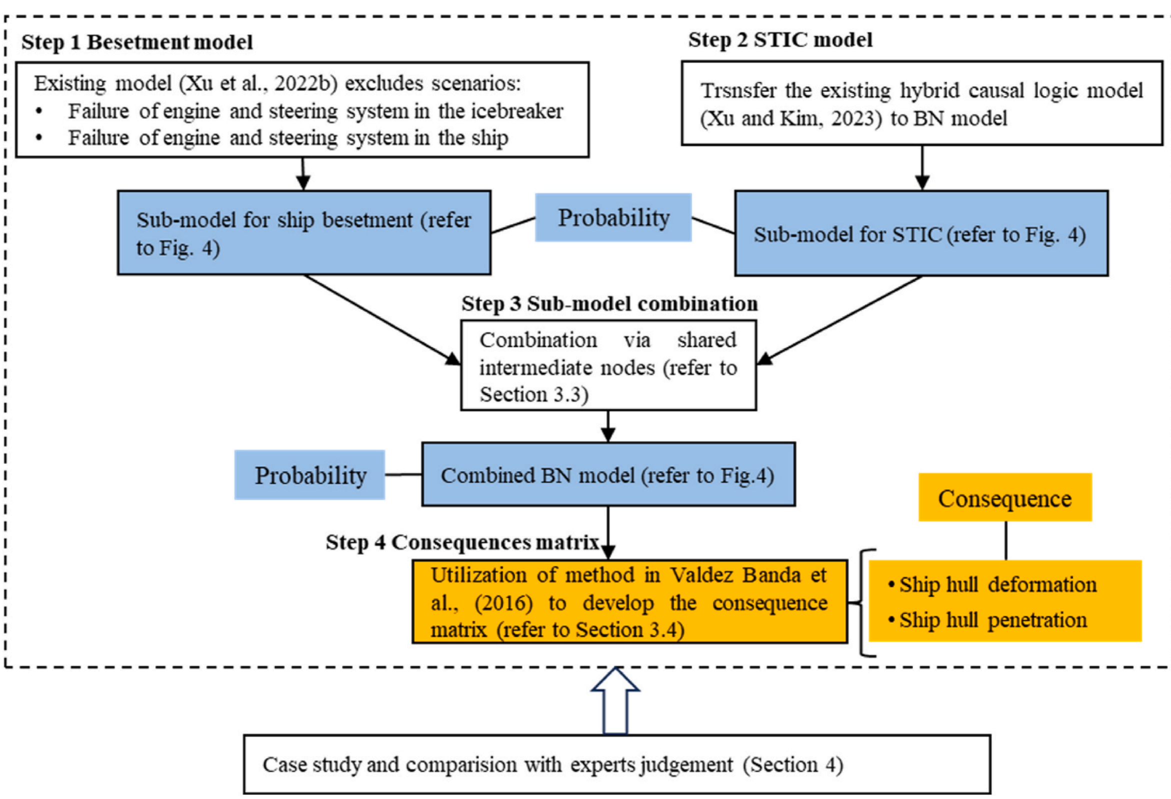

Fig. 3. Flowchart of the development of the integrated model. Details of the BN besetment model (Step 1) are given in Xu et al. (2022b) and of the hybrid causal logic model (Step 2) Xu and Kim (2023).

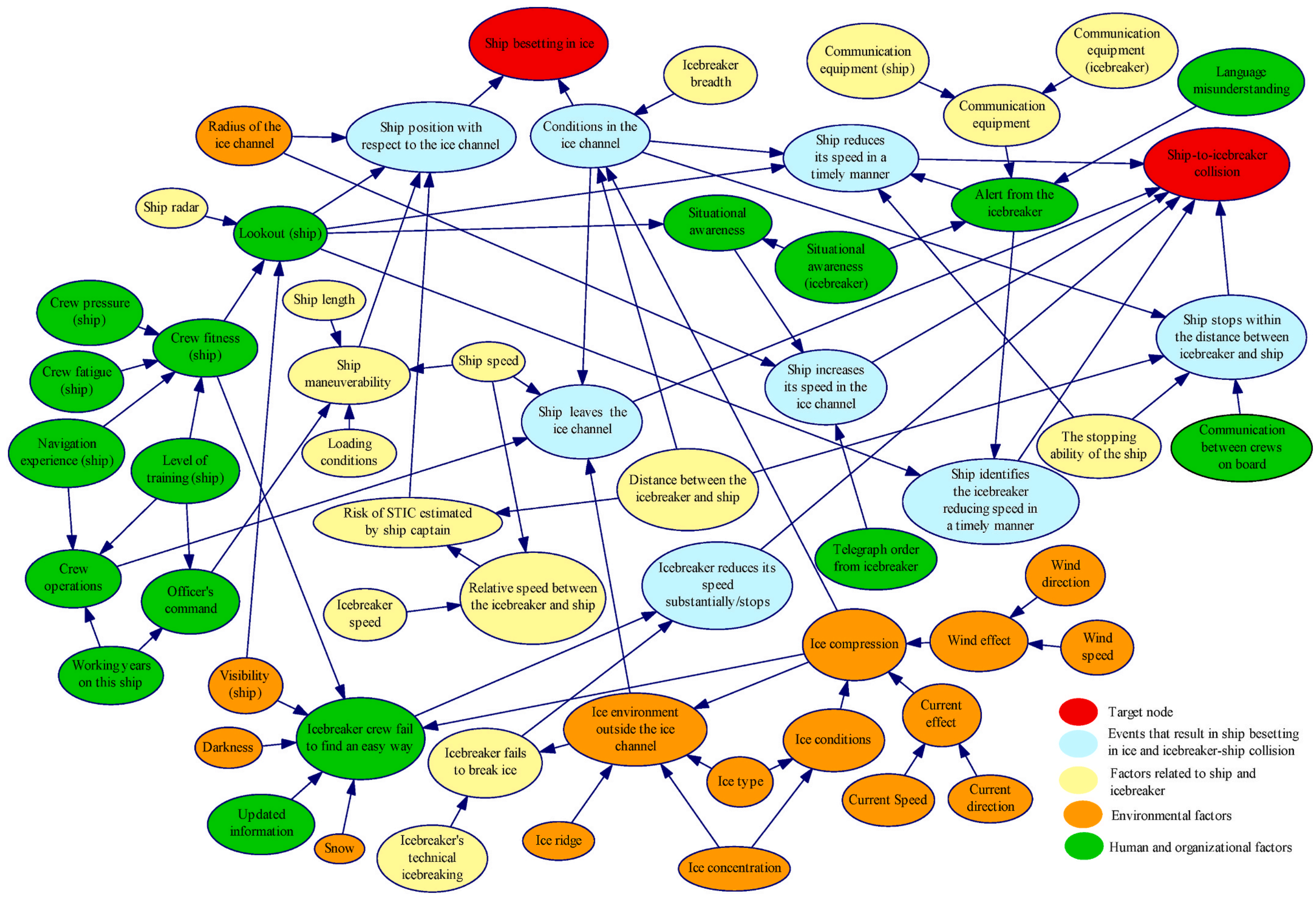

Fig. 4. The combined Bayesian network for estimating the risk of escort operations.

channel based on four icebreaker captains' elicitation and verification. To combine this model with the developed BN besetment model, the HCL was transferred to the BN model based on the work of Bobbio et al. (2001) and Khakzad et al. (2013). The mapping from the FT and ESD into the BN is illustrated in Fig. 5.

- Transfer the FT to the BN

The methodology of mapping from an FT into a BN encompasses both graphical and numerical translations (Bobbio et al., 2001; Khakzad et al., 2013). In the graphical step, the BN structure is constructed from the FT, wherein the basic and intermediate events, along with the top event, are represented as root nodes, intermediate nodes, and target nodes, respectively, in the BN. The interconnectivity of the nodes in the BN corresponds to that of the events in the FT. The graphical mapping is illustrated in Fig. 5. The subsequent numerical step entails assigning prior probabilities of occurrence to the basic events, which correspond to the corresponding root nodes in the BN. For the intermediate and target nodes, a conditional probability table (CPT) is allocated, which explicates the relationship between the intermediate nodes and their respective predecessor root and intermediate nodes.

- Transfer the ESD to the BN

The process of mapping from an ESD into a BN is based primarily on the work of Bearfield and Marsh (2005). It involves the representation of each initiating event (IE) and pivotal event (PE) of the ESD by an intermediate node that possesses two states, one for the failure and the other for the success of the IE/PE. Additionally, a target node is included in the BN, with a number of states equivalent to the number of ESD consequences. The intermediate node IN_i is linked to its preceding intermediate node IN_{i-1} only when the failure probability of IN_i depends on whether IN_{i-1} has succeeded or failed. In other words, the connection between IN_i and IN_{i-1} is established only when $P(IN_i|\, IN_{i-1}) \neq P(IN_i|\, \overline{IN}_{i-1})$. Analogously, the intermediate node IN_{i+1} must be linked to IN_{i-1} if the failure probability of IN_{i+1} depends on IN_{i-1}. Moreover, a connection between each intermediate node and the target node is established only if the state probabilities of the target node are influenced by the intermediate nodes' success or failure. After the BN is constructed, the prior probabilities of intermediate nodes are regarded as the probabilities of IEs and PEs, and a CPT is assigned to the target node as well as to the intermediate nodes. Notably, while the CPT of the target node performs like a logical AND-gate, the CPTs allocated to the intermediate nodes represent simple causal relationships, different from logical AND and OR-gates frequently encountered in FT-based BNs.

- Transfer of the HCL to the BN

In the developed HCL model, the IEs and PEs were analyzed by FT and/or BN. Thus, the target nodes transferred from FT are represented as intermediate nodes. The end states of the ESD are transferred into the target node of the BN. Fig. 5 illustrates the mapping algorithm of FT and ESD into BN, and the transferred BN model is illustrated in Fig. 4.

3.3. Combining the besetment model and STIC model

The combination was facilitated by the presence of intermediate nodes shared by both models in Xu et al. (2022b) and in Xu and Kim

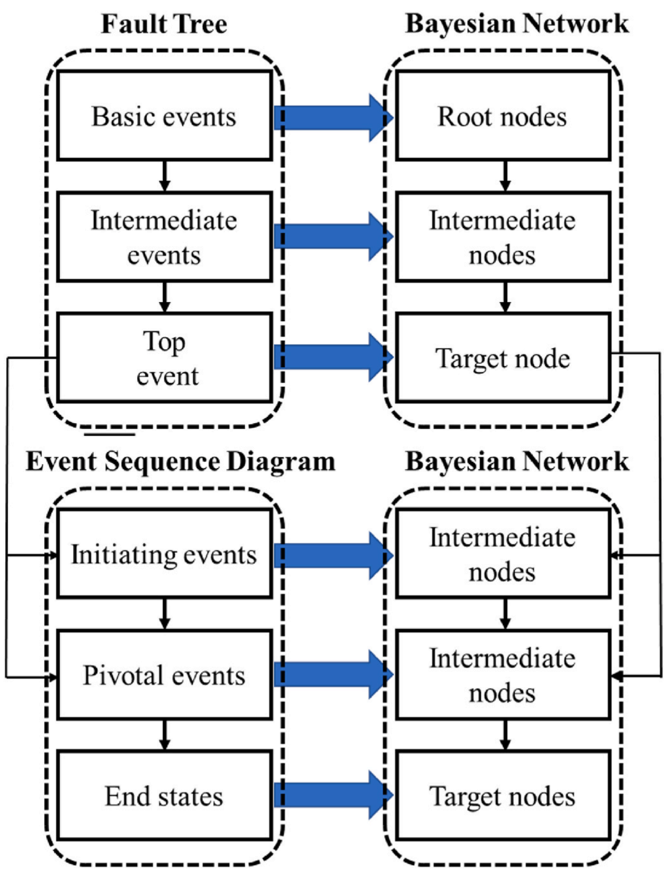

Fig. 5. Mapping algorithm from the FT and ESD (in Xu and Kim, 2023) into the BN (Fig. 4).

(2023). Taking the intermediate node "conditions in the ice channel" as an example, the combination process is illustrated in Fig. 6.

3.4. Consequences

3.4.1. The consequences of ITSC during cutting ship loose operation

In situations where an assisted ship becomes beset in ice, the icebreaker may choose to navigate out of the ice channel ahead of the beset vessel and then travel back along the ice channel line, swinging around astern and crossing the bows at an angle of approximately 30° from the ship's heading (Buysse, 2007). The icebreaker may pass very closely alongside the beset vessel. The most common methods of breaking a ship free from ice are the sternboard mode, forward mode, and quarter pass, which depend on factors such as ice thickness and pressure, wind direction, traffic density, and other relevant conditions. For further details on these different modes, refer to Buysse (2007).

The angle of collision indicates the possible angle of collision on the collision point. According to the aforementioned description of cutting loose operation and the research (Valdez Banda et al., 2016), the possible angle of collision in breaking loose operations is illustrated in Fig. 7. The typical deadweight tonnage (DWT) of icebreakers (including Yamal, 50 Let Pobedy, Taymyr, and Vaygach) along the Northern Sea Route is approximately 4K DWT. From Fig. 2, the minimum DWT that causes hull penetration is 5K DWT only at a collision angle of 90° and a speed over 9 knots. Therefore, the consequence of ITSC is regarded as hull deformation in this study considering the low speed (Buysse, 2007) and smaller DWT.

3.4.2. The consequences of STIC in ice channel

In the escort operation, the possible angle of collision is related to the icebreaker breadth the distance between the icebreaker and ship, and the calculation of angle of collision is shown in Fig. 8 (a) and result is shown in Fig. 8 (b).

Fig. 2 shows that this ship could penetrate a single-hull tanker at different speeds and collision angles (e.g., a speed of 3 kn and collision angle of 30°), which are marked with wheat color. If a vessel with a DWT below 40K can cause hull penetration, then under equivalent conditions, vessels with a DWT greater than 40K can also cause hull penetration. Based on this hypothesis, the consequence of metrics for the STIC is displayed in Fig. 9.

In the case study detailed in Section 4, the DWT of the assisted ship is approximately 40K. The icebreaker breadth is 30 m, and the distance between the icebreaker and ship ranges from 612 m to 1132 m. Consequently, the angle α is less than 5° according to the calculation in Fig. 8(a). According to the consequence metrics shown in Fig. 9, the consequence could be ship hull deformation (only when the collision speed is less than or equal 1 kn, and the angle of collision is not 90°), or ship hull penetration. To facilitate the presentation of the consequences of STIC, ship hull penetration is used in Section 4.3.1.

4. Case study

4.1. Assessment of an escort operation

To assess the feasibility of the model (i.e., probability estimation), the model was applied to the voyage of a ship (FS Ice Class 1A) along the Northeast Passage in August 2015. The voyage track is shown in Fig. 10, and the details of this voyage are elaborated below.

The escort operation commenced at 161°2.2′ E, 72°36′ N (WGS84) on August 5, 2015 and ended at 136°48.9′ E, 74°18.8′ N (WGS84) on August 7, 2015 (see Fig. 10).

4.1.1. Input data

To apply the proposed model, six waypoints containing sufficient information for populating the developed model were identified from the logbook and automatic identification system (AIS) data, which were provided by COSCO SHIPPING Specialized Carriers Co., Ltd. (ref. Table 2). The details of the sources of the basic factors are explained as follows:

- Factors related to the ship and the icebreaker

The failure probability of ship radar was assumed to be 1×10^{-3} (Xu et al., 2022b), and the probability of failure of the communication equipment of the icebreaker and ship was considered to be 7×10^{-4} (Baksh et al., 2018). The stopping ability of the ship is indicated by its speed. The distance, D, between the icebreaker and the ship was computed based on their respective geographic coordinates. The latitude and longitude of the icebreaker and ship were obtained from AIS data. The icebreaker can break ice up to 2.5 m, and the failure of icebreaking is estimated based on the derived ice thickness along the voyage, based on data from Copernicus's ARCTIC_REANALYSIS_PHYS_002_003 (Copernicus Marine Service, 2022).

- Human and organizational factors

The probability of an incorrect/inappropriate telegraph order from the icebreaker to the ship was considered to be 8×10^{-4} (Kum and Sahin, 2015). The situational awareness of the icebreaker is assumed to be sufficient. The lack of updated information for navigation may steer the ship operator toward an incorrect route, although the likelihood of this was estimated to be quite low, at 5.3×10^{-4} (Baksh et al., 2018). The working language between the icebreaker and the ship is English (IMO, 2001), and crew members from different countries may have different accents and cultures, which can further lead to communication misunderstanding, which was assumed to be low, i.e., 7×10^{-4} (TÖZ et al., 2021). On the assisted ship, all crews were from the same country;

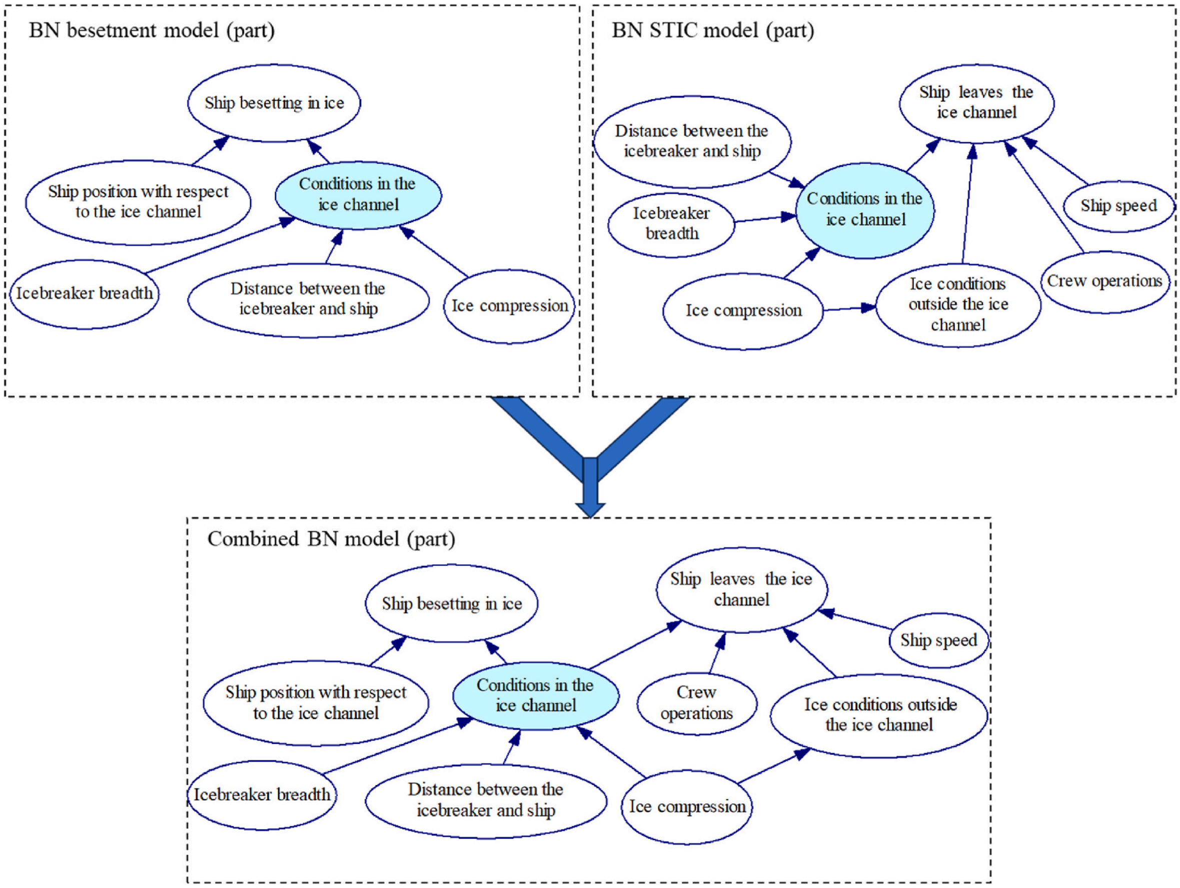

Fig. 6. Example of combining model parts through shared intermediate nodes (e.g., conditions in the ice channel).

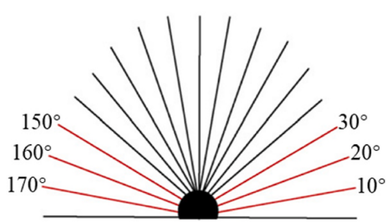

Fig. 7. Possible angle of collision in breaking loose operation, [10°, 30°], [150°, 170°] (Valdez Banda et al., 2016).

therefore, the communication between crews was considered "efficient". According to the captain-written report, all crew members underwent extra training before commencing their Arctic voyages, and the bridge team had ice navigation experience. The states of crew fatigue and crew pressure were assumed to be low in this study.

- Environmental factors

The ice environment outside the channel are reflected by the ice type, ice concentration, presence of ice ridges, and ice compression. The ice concentration and type were derived from the records of the voyage logbook and using Arctic Ocean Physics Reanalysis data (Copernicus Marine Service, 2022). Ice ridging is dominated by the ice concentration. The frequently quoted ice concentration threshold for ridging is 0.8 (Løset et al., 2006). Because the voyage occurred during summer, the ice along the coastline had melted. Therefore, ice compression, snow, and darkness were not considered. The radius of the ice channel was assumed to be sufficient according to the trajectory in Fig. 9. The visibility information was collected from the ship's logbook.

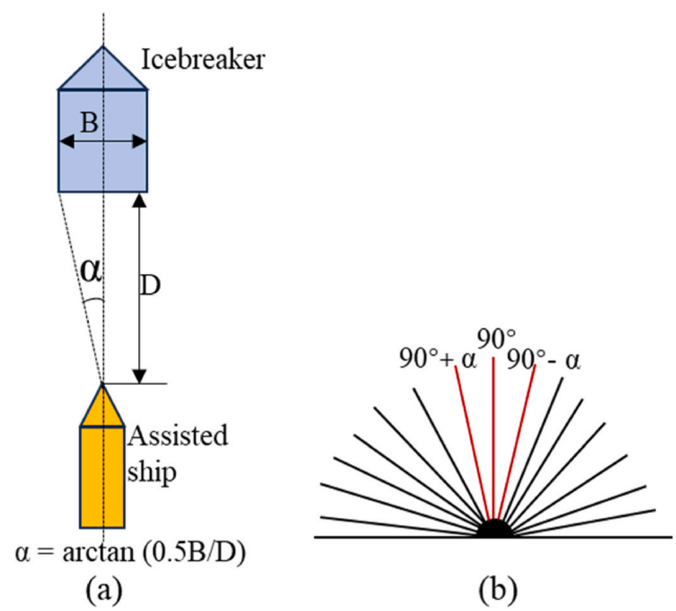

Fig. 8. Possible angles of collision in an ice channel in an escort operation, [90°-α, 90°+α], B is the icebreaker breadth, D is distance between the icebreaker and ship.

4.2. Assessment of escort operations by experts

The model's viability is further substantiated through a comparison of its outputs with expert judgments in 14 specific scenarios. These

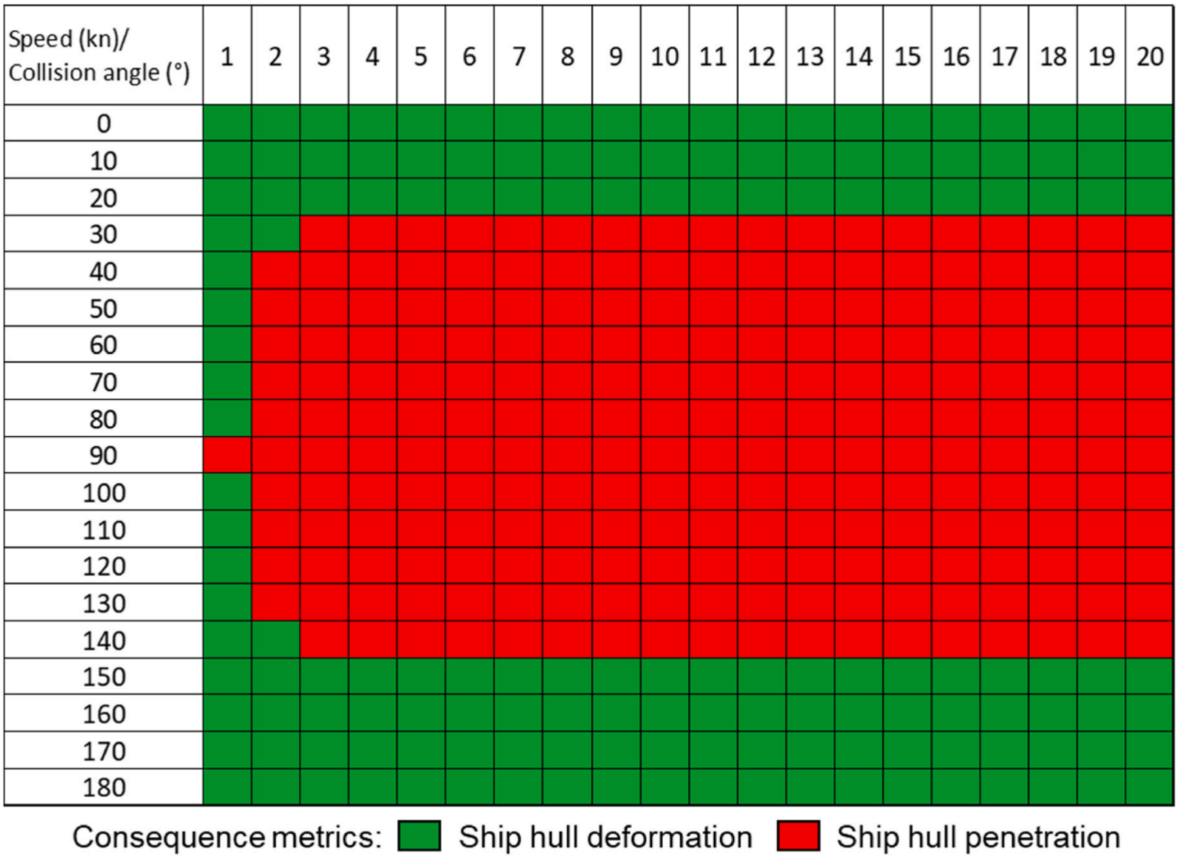

Fig. 9. Consequence metrics for a STIC (the assisted ship is 40K DWT).

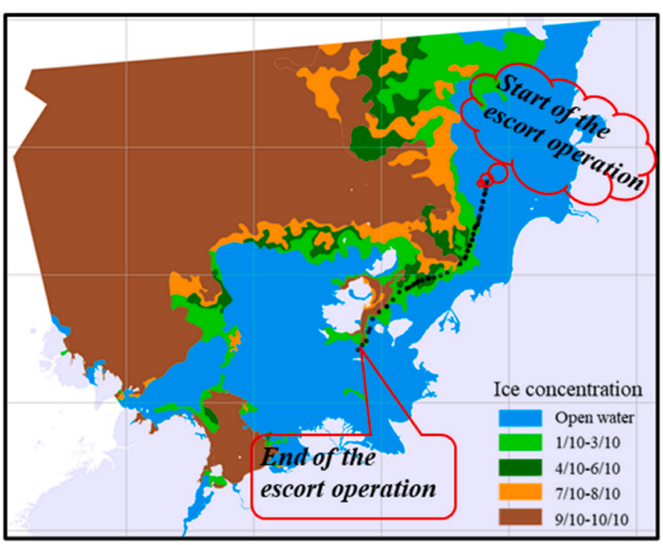

Fig. 10. Trajectory of the escort operation, plotted on the top of the ice chart from (AARI).

scenarios, along with the accompanying expert elicitation questionnaire, are provided in Appendix A. The questionnaire was structured into three sections. The initial segment gathers fundamental information about the captain, including their years of experience in ice navigation and whether they have undergone ice navigation training. The second section outlines the developed BN model and the risk factors under consideration. The final section comprises the 14 scenarios and prompts the experts to estimate the likelihood of ship besetting in ice and STIC. Further details of the questionnaire can be found in Appendix A.

4.3. Results

4.3.1. Results of the case study

The calculated probabilities of a ship besetting in ice and a STIC are illustrated in Fig. 11. Notably, the probability of ships getting stuck in ice remained relatively stable (at approximately 30%). Please note that the presented probability numbers should be treated as levels of occurrence, and thus differ from frequencies, which are statistically calculated based on accident data. For example, in WP 2 and WP 5, the probabilities of STIC are considerably high compared to those of other waypoints. According to the logbook, in WP 2, the icebreaker escorted the ship with several turns to avoid large ice floes. In WP 5, the visibility deteriorated, and the distance between the icebreaker and the ship was 0.5 nm, contributing to the higher collision probability.

During risk assessment, the consequences of injury or damage to the health of people, damage to the environment or other assets are generally converted into a common unit, e.g., dollar value (Khan et al., 2014). As discussed in Section 3.4, the consequences associated with ITSC is hull deformation and STIC are ship hull penetration. To simplify the representation of risk level (probability * consequences), the value of 50 was assigned to ship hull deformation and 100 to ship hull penetration. The results of the risk level are illustrated in Fig. 12. Notably, when calculating the risk level of a ship besetting in ice, the probability of the ITSC should be considered, and it was assumed to be 0.2. A further discussion of the probability of the icebreaker colliding with the beset ship is presented in Section 5.2.

4.3.2. Model comparison with expert judgment

We received six pieces of feedback from the captains, and the results of the expert judgment and the model output are presented in Table 3

Table 2
The input evidence of basic nodes for six waypoints (WPs).

		WP 1	WP 2	WP 3	WP 4	WP 5	WP 6
Factors related to ship and icebreaker	Ship speed	High	High	Medium	Medium	Medium	High
	Ship length	Medium	Medium	Medium	Medium	Medium	Medium
	Loading conditions	Fully loaded	Fully loaded	Fully loaded	Fully loaded	Fully loaded	Fully loaded
	Ship radar[b]	Failure: 1×10^{-6}	Failure: 1×10^{-6}	Failure: 1×10^{-6}	Failure: 1×10^{-6}	Failure: 1×10^{-6}	Failure: 1×10^{-6}
	Stopping ability of the ship	Low	Low	Medium	Medium	Medium	Low
	Communication equipment (ship)	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 7×10^{-4}
	Communication equipment (icebreaker)	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 5.6×10^{-2}	Failure: 7×10^{-4}
	Icebreaker breadth	Large	Large	Large	Large	Large	Large
	Icebreaker's technical icebreaking	High	High	High	High	High	High
	Icebreaker speed	High	High	Medium	Medium	Medium	High
	Distance between the icebreaker and the ship	Long	Medium	Long	Long	Medium	Long
Human and organizational factors	[a]Crew pressure (ship)	Low	Low	Low	Low	Low	Low
	[a]Crew fatigue (ship)	Low	Low	Low	Low	Low	Low
	Navigation experience (ship)	Medium	Medium	Medium	Medium	Medium	Medium
	Level of training (ship)	Extra	Extra	Extra	Extra	Extra	Extra
	Working years on this ship	High	High	High	High	High	High
	Communication between crews on board	Efficient	Efficient	Efficient	Efficient	Efficient	Efficient
	Telegraph order from the icebreaker	Unsuitable/ wrong: 8×10^{-4}	Unsuitable/ wrong: 8×10^{-4}	Unsuitable/ wrong: 8×10^{-4}	Unsuitable/ wrong: 8×10^{-4}	Unsuitable/ wrong: 8×10^{-4}	Unsuitable/ wrong: 8×10^{-4}
	[a]Situational awareness (icebreaker)	Sufficient	Sufficient	Sufficient	Sufficient	Sufficient	Sufficient
	Updated information	Lacking: 5.3×10^{-4}	Lacking: 5.3×10^{-4}	Lacking: 5.3×10^{-4}	Lacking: 5.3×10^{-4}	Lacking: 5.3×10^{-4}	Lacking: 5.3×10^{-4}
	Language misunderstanding	7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}
Environmental factors	Radius of ice channel	Sufficient	Sufficient	Sufficient	Sufficient	Sufficient	Sufficient
	Ice concentration	Low	Medium	Low	Medium	Low	Medium
	Ice type	Light	Light	Light	Light	Light	Light
	Ice compression	None	None	None	None	None	None
	Ice ridge	No	No	No	No	No	No
	Visibility (ship)	Good	Good	Good	Good	Bad	Good
	Darkness	No	No	No	No	No	No
	Snow	No	No	No	No	No	No

[a] The states of the variables are assumed.
[b] The failure probability considers the equipment redundancy.

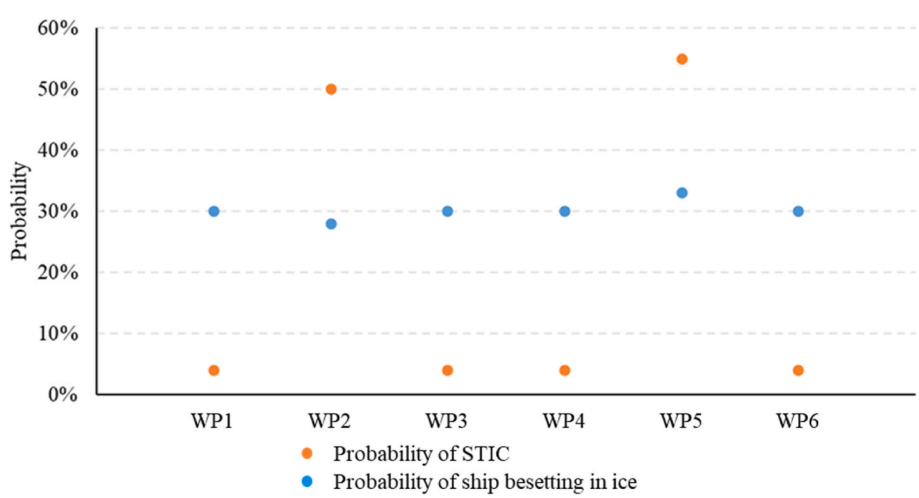

Fig. 11. The probabilities of ship besetting and STIC.

and Figs. 13 and 14.

- Scenarios 2-4

Ship besetting in ice: In terms of expert estimation, there is a 4% difference between Scenarios 2 and 4, while there is a much larger 37% difference between Scenarios 3 and 4. This indicates that experts believe that ice concentration and ice ridges have a greater impact on ship besetment probability than does ice thickness. The model's output shows a 1% difference between Scenarios 2 and 4 and an 11% difference between Scenarios 3 and 4, which aligns with the experts' views. Notably, in Scenario 3, the variation among the six experts' judgments is

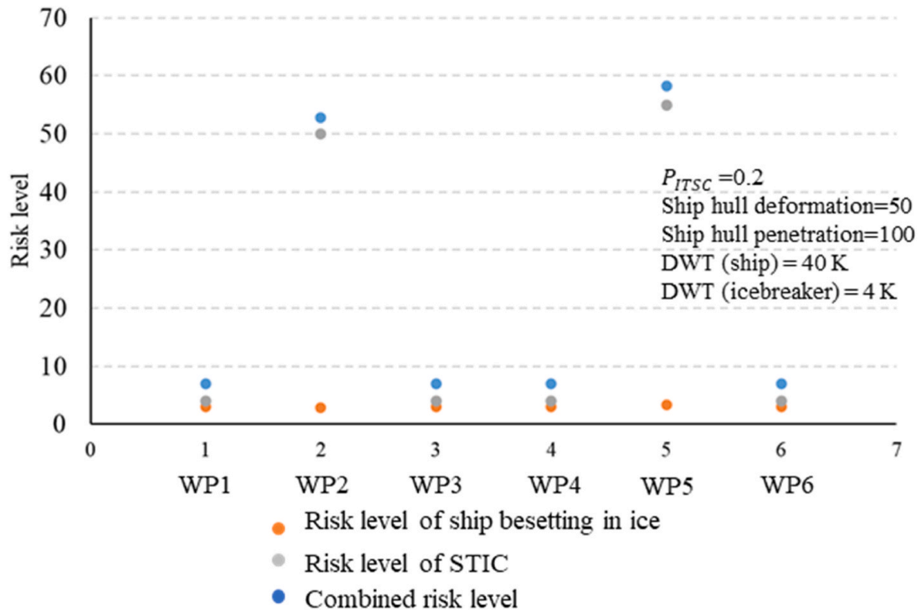

Fig. 12. The risk level of ship besetting and STIC (the calculation is based on the equation $CRL = P_b \times P_{ITSC} \times C_b + P_c \times C_c$; for details, refer to Section 5.2).

Table 3
Probability of ship besetting in ice and STIC estimated by the developed model and experts.

Scenario No.	Probability of ship besetting in ice		Probability of ship colliding with the icebreaker	
	Expert judgment	Model output	Expert judgment	Model output
S 1	30%	32%	26%	20%
S 2	52%	41%	47%	35%
S 3	11%	29%	17%	41%
S 4	48%	40%	25%	33%
S 5	34%	33%	11%	25%
S 6	23%	33%	43%	52%
S 7	39%	35%	33%	57%
S 8	18%	37%	15%	10%
S 9	31%	33%	32%	52%
S 10	38%	38%	43%	52%
S 11	13%	31%	39%	20%
S 12	21%	32%	52%	53%
S 13	44%	38%	16%	3%
S 14	35%	37%	9%	1%

minimal, with absolute differences not exceeding 10%.

STIC: The most significant difference between the model output and expert judgment is seen in Scenario 3, with a notable discrepancy of 24%. Experts' assessments show a 22% difference in probability between Scenarios 2 and 4, while the difference between Scenarios 3 and 4 is 8%. This suggests that experts place greater emphasis on ice thickness than ice concentration in terms of collision occurrence, likely because thicker ice might impede the ship's ability to navigate away from the icebreaker and avoid a collision.

- Scenarios 5-7

Ship besetting in ice: In regard to the ship besetting in ice, there is congruence between the model outputs and the expert judgment. By contrasting the difference in probability assessed by experts between Scenarios 5 and 7 (5%) with that between Scenarios 6 and 7 (16%), as illustrated in Fig. 13 (c) and (d), it becomes apparent that experts assign significance to the radius of the ice channel as a determining factor for ship besetment in comparison to visibility. According to the model output, the difference in probability between Scenarios 5 and 7 is 2%, and that between Scenarios 6 and 7 is 2%, indicating that visibility and the ice channel radius hold equal importance in the proposed model.

STIC: Experts assessed a 22% difference in probability between Scenarios 5 and 7 and a 10% difference between Scenarios 6 and 7. This suggests that experts prioritize visibility over the radius of the ice channel when determining collision probabilities. The model outputs indicate a 32% difference in probability between Scenarios 5 and 7 and a 5% difference between Scenarios 6 and 7, which agree with experts' perceptions.

- Scenarios 8-10

Ship besetting in ice: There is a similarity in probability between the model and expert evaluations in Scenarios 9 and 10, whereas a disparity emerges in Scenario 8; see Fig. 14 (e) and (f). Regarding the experts' judgment, the difference in probability between Scenarios 8 and 10 is 20%, while that between Scenarios 9 and 10 is 7%. This result indicates that the experts perceive that visibility is more important than navigation experience. According to the model output, the difference in probability between Scenarios 8 and 10 is 42%, and that between Scenarios 9 and 10 is 0%. The model also agrees with experts' perceptions.

STIC: Scenario 9 displays a greater difference between expert judgment and the model compared to Scenarios 8 and 10. Regarding expert judgment, the difference in probability between Scenarios 8 and 10 is 28%, and that between Scenarios 9 and 10 is 11%, which implies that experts also place a higher importance on visibility than navigation experience when evaluating collision probabilities.

- Scenarios 11-14

Ship besetting in ice: Regarding the probability of a ship besetting in ice, the difference between the model output and expert judgments is minor in Scenario 14 (2%), small in Scenario 13 (6%), and large in Scenario (18%), as presented in Fig. 14 (g) and (h). Regarding experts' judgment, the difference in probability between Scenarios 11 and 14 is 22%, while that between Scenarios 13 and 14 is 9%. It appears that experts perceive the influence of distance to have a more substantial impact on ship besetment compared to visibility. The model's output shows that the difference in probability between Scenarios 11 and 14 is 19% and that between Scenarios 13 and 14 is 2%, which aligns with the experts' views.

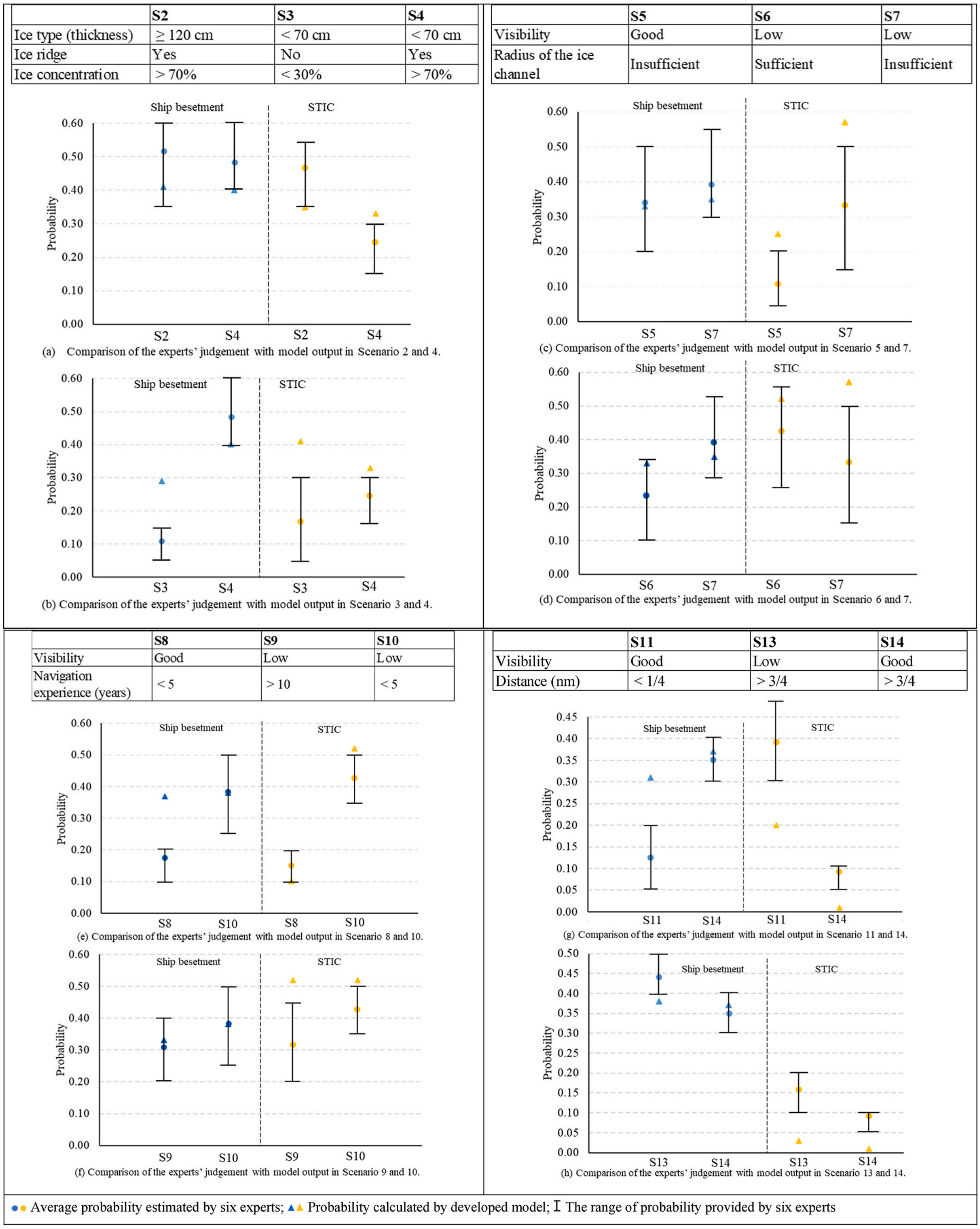

Fig. 13. Comparison of expert judgment and model output for designed scenarios.

STIC: For collision risk, there is a notable similarity in the probability trends (refer to Table 3 and Fig. 14) in both expert judgments and model outputs. This suggests that there is agreement between expert judgment and the model's estimates of collision risk, taking into account the distance and visibility. A further discussion on the distance and visibility is provided in Section 5.3.

- Summary

The results of ship besetment, as depicted in Fig. 14, show strong alignment between the probability trends calculated by the proposed model and the experts' assessments. However, the trend between Scenarios 8 and 9 diverges due to the experts' belief that visibility holds greater importance than navigation experience.

In the STIC estimation, there are three instances of contrasting trends between the model output and expert judgment. The first two occur in Scenarios 2 and 3 and Scenarios 3 and 4. This is due to experts considering ice thickness to be more critical than ice concentration, as discussed earlier. The third opposite trend is observed in Scenarios 6 and 7, driven by the experts' belief that visibility surpasses the radius of the ice

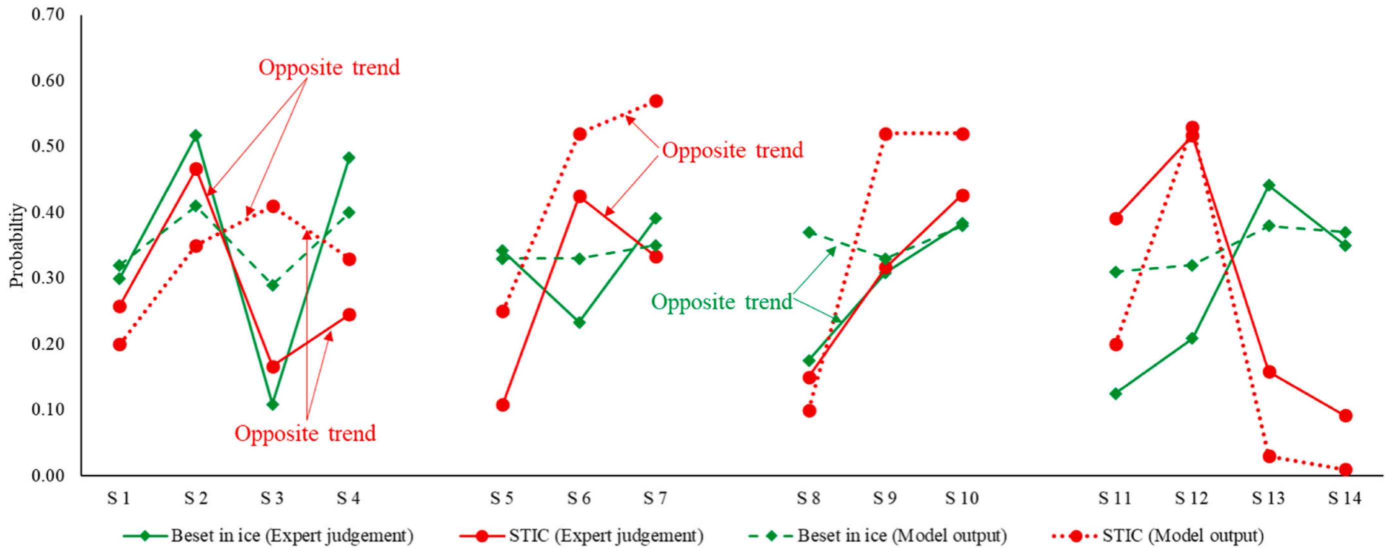

Fig. 14. Results of expert judgment and model output for designed scenarios.

channel in terms of importance in STIC.

5. Discussion

5.1. Model validation

Model validation is a crucial process to enhance the credibility of a developed model, particularly when it relies on subjective judgment. While the validity of a BN for a physical phenomenon such as an STIC can typically be assessed by validating it against extensive voyage data, this approach presents challenges in the context of escort operations in the Arctic for several reasons. First, a scarcity of accident reports related to ship besetting and STIC limits the accessibility of experimental databases for testing the model's performance. Second, previous research has not fully encompassed the combined risk, including the risks of both ship besetting in ice and STIC. Last, the risk of ship besetting is not consistently recognized as a hazardous event in certain accident record systems (Xu et al., 2021), but it is essential to consider in practical operations.

Therefore, in this study, the validation framework introduced by Pitchforth and Mengersen (2013) is adopted. This framework encompasses four aspects of validity: face validity, content validity, concurrent validity, and predictive validity. In the following section, these validity measures will be outlined in detail.

5.1.1. Face validity

The models concerning the probabilities of ship besetting in ice and STIC were developed based on the ice navigation experience of the first author, discussions between authors, the literature, and expert judgment. The risk factors and structure of the underlying models for besetment and STIC were validated by captains from merchant and icebreaker ships. The consequences of the models were derived from previous research considering ship speed, ship tonnage, and collision angle. The results of the consequences (see Section 3.4) in this study are in line with the findings in previous reports (Risto Jalonen et al., 2005; Franck and Holm Roos, 2013). Therefore, the face validity for the rationality and consistency of the developed model was considered to be high.

5.1.2. Content validity

The content validity pertains to the nodes considered and the discretization of nodes (Pitchforth and Mengersen, 2013). The content validity of the probability model concerning ship besetting was examined in Xu et al. (2022b). For the model predicting the probability of STIC, a comparison between the crucial risk factors identified in the model (as outlined in Section 5.1.4) and those identified in earlier research is presented in Table 4. Evidently, the significant risk factors recognized in the proposed model are consistent with the literature.

Moreover, this model introduces novel risk factors such as ice compression, ice channel conditions, level of training, navigation experience, and years of experience on the ship. These novel factors were suggested based on the first author's ice navigation experience, discussions among the authors, and insights gleaned from elicitation

Table 4
Comparison of identified important factors in each study.

Ref.	Identified important factors		
	Technical factors related to the ship and icebreaker	Environmental factors	Human and organizational factors
This Study	1) Distance 2) Ship/icebreaker speed 3) Radius of the ice channel	1) Ice compression 2) Visibility	1) Navigation experience 2) Telegraph order from the icebreaker 3) Situational awareness (icebreaker) 4) Communication between crews on board
Guo et al., 2023	1) Ship speed 2) Distance	1) Ice conditions 2) Existence of ice ridges[a] 3) Bad visibility	1) Improper route selection
Franck and Holm Roos (2013)	1) Short distance 2) Ship speed	1) Severe ice conditions	1) Communication between icebreaker and ship
Valdez Banda et al. (2015)	1) Distance	1) Existence of ice ridges[a] 2) Level ice with thicknesses between 0.15 m and 0.4 m 3) Low temperatures (−20 °C to −40 °C).	No

[a] As interpreted in this study.

with captains. These enrichments contribute to making the model more reflective of actual operational scenarios, enhancing its authenticity.

The discretization of nodes followed two primary criteria:

- Limit the number of states to three to fulfill data requirements and prevent exponential growth of the CPT with increasing states (Rausand and Haugen, 2020).
- The variable's states were established as either binary (such as "yes" and "no" for the variable "ship besetting in ice") or numerical values (for example, the states reflecting "crew fatigue" were defined based on working hours following the crew shift change). Concerning the states represented numerically, the fundamental concept is that each state holds a comparable numerical duration. Consider the instance of "crew fatigue". This variable was discretized into three states (i.e., severe, moderate, and light), and the officer's shift was 4 h. Consequently, one-third of the shift duration (1.3 h) was employed to ascertain the numerical duration for each state.

5.1.3. Concurrent validity

Due to the lack of published models for calculating the combined risk of escort operations in ice-covered waters, it is not possible to assess the concurrent validity of the newly developed model.

5.1.4. Sensitivity analysis

A sensitivity analysis aims to gauge how alterations in the basic node influence changes in the target node, as outlined by Hegde et al. (2018). When a minor change in a basic node leads to a significant alteration in the target node, the target node is deemed sensitive to this basic node. Identifying these sensitive nodes equips BN users with insights into the factors' impact, potentially causing ship besetment in ice and ship colliding with the icebreaker.

In this study, the variation in the probability of the target node (VPTN) is employed to quantify the sensitivity extent of a basic node with respect to the target node. VPTN represents the absolute probability difference of a particular state in the target node due to a change in the basic node from one state to another. The detailed procedures can be found in Xu et al. (2022a). The results are summarized in Fig. 15.

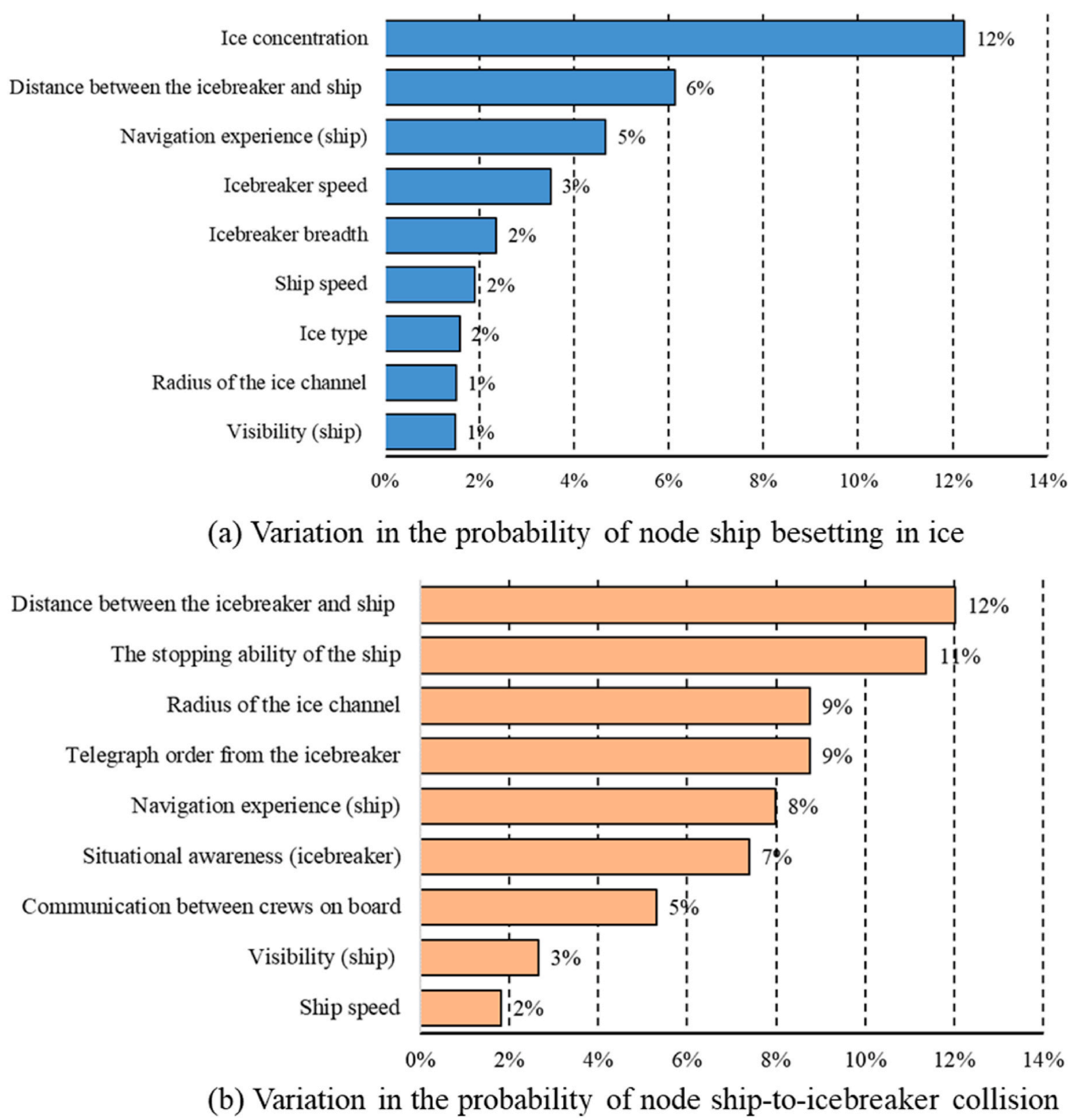

Fig. 15. Sensitivity of each factor to the target node. (a) For the target node "ship besetting in ice". (b) For the target node "ship-to-icebreaker collision".

- For the target node "ship besetting in ice", ice concentration is the most important factor. The other two important factors are the distance between the icebreaker and the ship and the navigation experience (ship).
- For the target node "ship-to-icebreaker collision", the distance and the stopping ability of the ship (indicated by the ship speed in this study) are the most important factors. The radius of the ice channel is the most important environmental factor that contributes to STIC. Among the human factors, telegraph order from the icebreaker, navigation experience (ship), situational awareness (icebreaker), and communication between crews on board are the most important factors.

5.2. Combined risk level for escort operations

Section 4.3.1 presents the occurrence probabilities of ship besetting in ice and STIC. To illustrate the risk (probability*consequences) associated with escort operation, we take into account the consequences of ITSC in terms of hull deformation and STIC in terms of hull penetration (for details, refer to Section 3.4). We calculated the combined risk level (*CRL*) using Equation (2).

$$CRL = P_b \times P_{ITSC} \times C_b + P_c \times C_c \quad (2)$$

where P_b is the probability of the ship besetting in ice, C_b is the consequence of ITSC during a breaking loose operation, and P_{ITSC} is the probability of ITSC given the ship beset in ice. P_c is the probability of a STIC in an ice channel, and C_c is the consequence of STIC. In Equation (2), P_{ITSC} is not predefined, and to further assess the impact of P_{ITSC} on *CRL*, the results of *CRL* for six waypoints in the case study with varying P_{ITSC} values are presented in Fig. 16. Take WP 2 as an example: as P_{ITSC} increases, the contribution of ship besetment to the total risk level also increases. It is not surprising that when P_{ITSC} is small, the risk level (calculated as the probability multiplied by P_{ITSC} and multiplied by the risk index of hull deformation) associated with a ship besetting in ice is lower. Notably, P_{ITSC} is influenced by factors such as the icebreaker's speed, crew's operational proficiency, and ice conditions (Buysse, 2007). The data are not sufficient to suggest a value for P_{ITSC}; thus, further discussion on this topic is omitted herein.

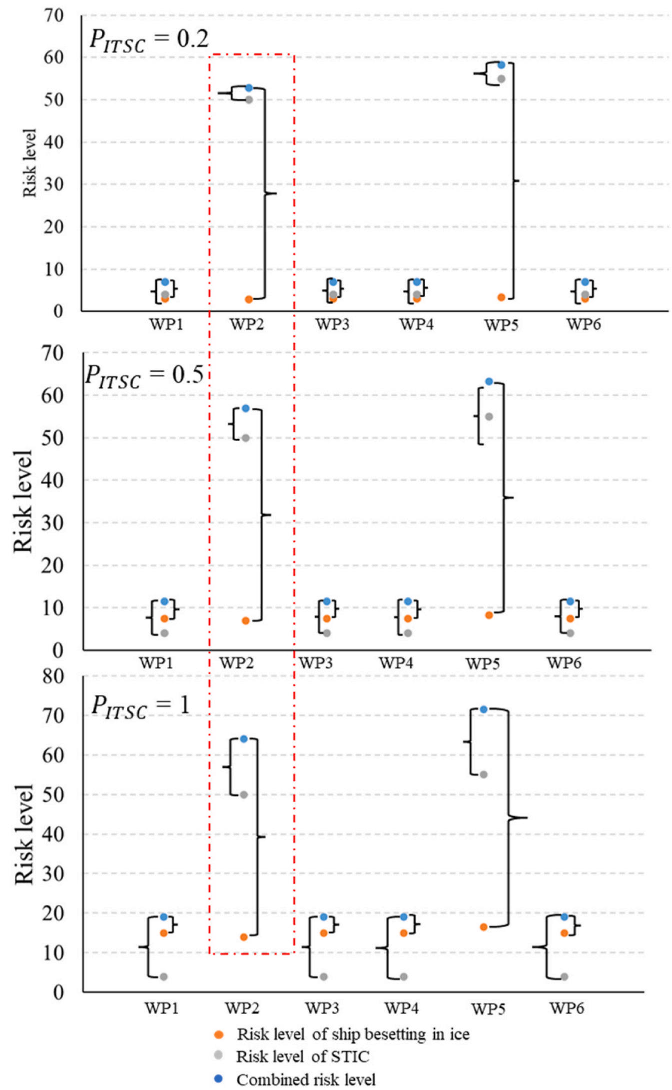

Fig. 16. Combined risk level considering different values of probability P_{ITSC}.

5.3. Distance in different visibility conditions

Navigation in low-visibility conditions presents challenges to maritime operations, particularly in escort/convoy operations. Low visibility significantly hampers a ship's ability to accurately perceive its surroundings. More than 40% of collision accidents stem from poor visibility (Gao, 2016). As gleaned from the expert judgment in Section 4.3.2 and the sensitivity analysis conducted in Section 5.1.4, visibility is a pivotal element in escort operations. This section undertakes an analysis of adjusting the distance to mitigate the combined risk in situations of reduced visibility.

During escort operations in ice-covered waters, as the distance between the icebreaker and the ship decreases, the probability of STIC increases. Conversely, as the distance increases, the probability of the ship besetting in ice rises. This implies the presence of a tradeoff in distance, which can be considered the 'optimal' distance where the probabilities of both ship besetting in ice and STIC are minimized. Fig. 17 illustrates the selection of the distance (three states) for scenarios of both good and low visibility. Under light ice conditions, as shown in Fig. 17 (a), it is advisable to maintain an extended distance, with further extension warranted in cases of reduced visibility. In contrast, under severe ice conditions, it is recommended to maintain a short to medium distance during good visibility and not to decrease this distance when visibility decreases. Notably, the extended distance during light ice conditions exceeds that in severe ice conditions, as shown in Fig. 17; however, determining the precise distance necessitates additional research.

5.4. Uncertainties analysis

The case study of the proposed model is carried out based on the evidence recorded in the ship's logbook, AIS data, and Copernicus Marine Service. The uncertainties of inaccuracies in expert judgment, data, and modeling procedures that may influence the results are considered. The ratings for uncertainty estimation were proposed by Flage and Aven (2009). The brief interpretation of the rating is shown in Table 5, and the estimation for the uncertainty of this study is shown in Table 6.

5.5. Limitations and future work

While the presented model provides insights into risk assessment for escort/convoy operations under Arctic conditions, it is important to acknowledge that the scope was limited to two specific risks: ships besetting in ice and STIC in the ice channel. Other risks, including economic considerations (e.g. delays costs by cutting loose maneuver) and ship-ice collisions, were not taken into account. The model developed for this study encompasses a comprehensive range of risk factors; nevertheless, its applicability to onboard ship operators might be challenging for inputting data for 31 basic nodes simultaneously. Thus, a prospective avenue of research could involve refining the model by

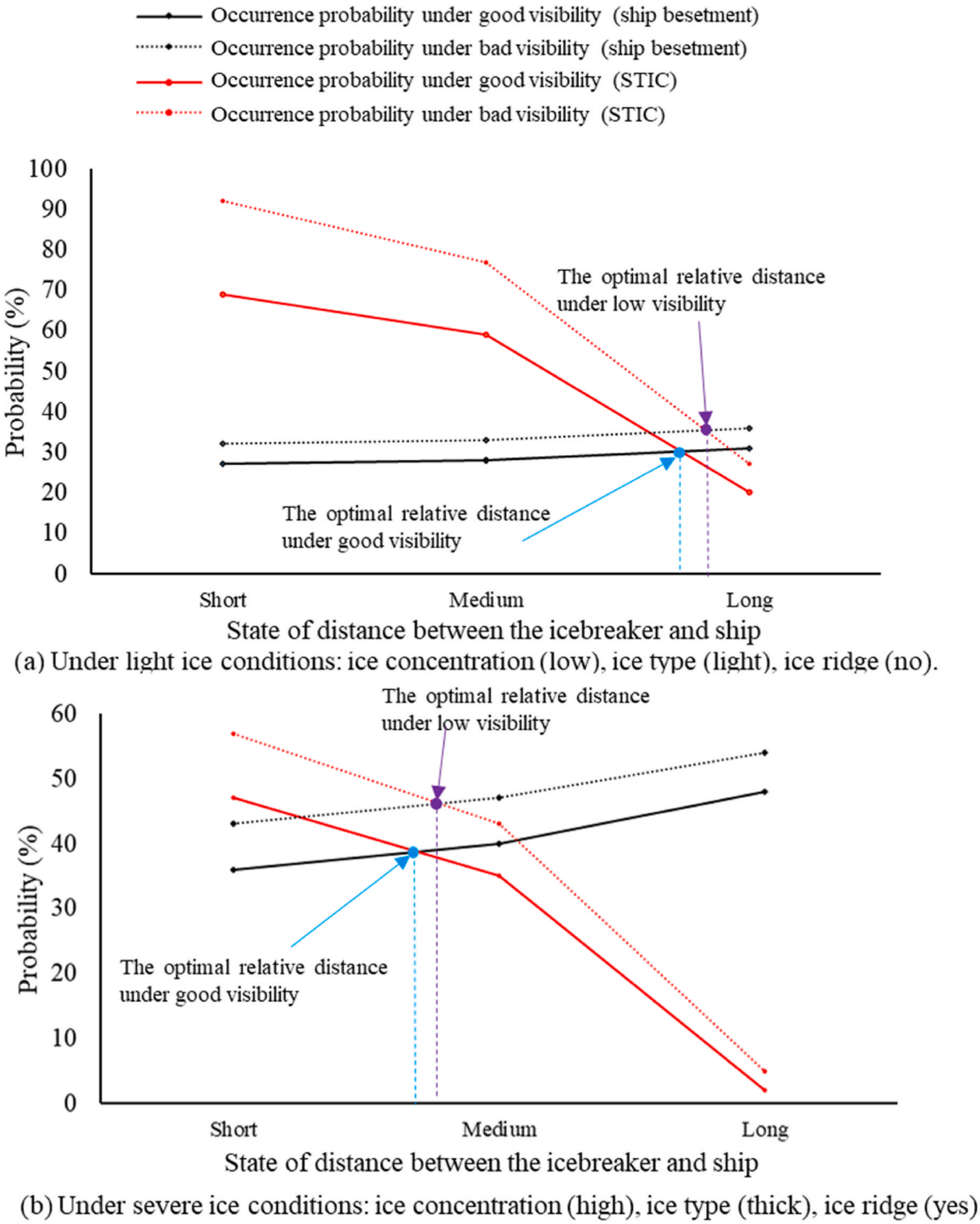

Fig. 17. The optimal distance under different visibility and ice conditions. Due to discretization of node "distance between the icebreaker and ship" in the BN model, the x-axis shows its three states, and the linear line only aims to indicate the probability trends (increase or decrease) rather than indicates the calculated results.

eliminating nodes with lower weights, as suggested by Xu et al. (2022a), and/or incorporating the critical factors identified in Section 5.1.4.

In the current model, the ice environment outside the ice channel evaluation includes information about total ice concentration, ice type (age/thickness), presence of ice ridges, and ice compression. While this perspective is grounded in academia, practical implementation may encounter a hurdle in terms of estimating the ice conditions, a concern highlighted by a captain in the questionnaire. To address this challenge, the integration of computer-aided scene analysis, e.g., Panchi et al. (2021, Panchi and Kim, 2024), into the risk model could provide additional information to the models, aiding ship operators in estimating the prevailing ice conditions during operations.

In this study, we used a consequence matrix for escort operations that was based on Fig. 2, but it does not take into account the unique bow shape of icebreakers. Consequently, the consequences caused by the icebreaker may be more extensive than those depicted in Fig. 2.

The model does not take into account the ratio between the breadth of icebreaker and the escorted ship and should be used with caution

Table 5
Interpretation of uncertainty ratings (Flage and Aven, 2009).

Aspect	Rating	Interpretation
Uncertainty	Low	Many reliable data are available; the phenomena involved are well understood, models are known to give predictions with the required accuracy.
	Moderate	Conditions between those characterizing low and high uncertainty.
	High	Conditions opposite to those characterizing low uncertainty.

Table 6
The uncertainty assessment for this study.

Uncertainty element	Rating	Justification
Input data	Moderate	The input data collected from the logbook, AIS, Copernicus Marine Service are recognized as trustworthy in Section 4.1.1. However, some inaccuracies may exist, as follows: Due to a lack of information regarding the icebreaker, the alleged statistics regarding the icebreaker (e.g., situational awareness) may contain some inaccuracies. The total number of waypoints (six) is not sufficient to fully showcase the versatility and effectiveness of the developed model. Regarding the ice thickness derived from the Copernicus data, due to the ice drift, the recorded ice thickness may differ from the actual ice thickness. It is recommended to include information about the ice as a part of the AIS message.
Model	Low	The model and the correlation between events/nodes in the model have been validated by five captains with substantial ice navigation experience. Furthermore, the model's output matches the expert judgments across 14 designed scenarios, albeit with minor discrepancies. Consequently, the uncertainty regarding the model's objective and variable correlation is low. Discretizing the node in the model into two or three states aims to mitigate the complexity of the CPT, yet it may introduces additional uncertainties to the results.
CPT determination	Low	The experts invited to estimate the CPT of BNs are Merchant Captains from COSCO group with Arctic navigation experience. As a result, the uncertainty in the CPT determination is regarded as low.
Consequences estimation	High	The consequences of ITSC relies on the likelihood of an icebreaker colliding with the assisted ship. Yet, there has been limited research on this probability, resulting in significant uncertainties when calculating the consequences. This lack of certainty stems from insufficient study; hence, it is strongly recommended to conduct further research in this area.

when the breadth of icebreaker and the escorted ship differ substantially.

6. Summary remarks and conclusions

This paper proposes a Bayesian network model to estimate the combined risk during escort/convoy operations in the Arctic while accounting for technical, environmental, human and organizational factors. Specifically, the proposed model comprises two components: estimation of the occurrence probabilities of ship besetting in ice and STIC, and estimation of their consequences in terms of hull deformation and hull penetration, respectively. The applicability of the model is demonstrated for a westbound voyage in August 2015 along the Northeast Passage. Furthermore, the probability calculations were compared with expert judgments across 14 specific scenarios covering ice conditions (ice concentration, ice thickness, and presence of ice ridging), visibility, navigation experience, distance between the icebreaker and the ship, and radius of the ice channel.

The main findings are summarized as follows.

- Through the combined BN model, it is found that the primary factor leading to ship besetting in ice is the ice concentration, whereas the distance between the icebreaker and the ship is the key factor influencing STIC.
- Experts place more emphasis on the radius of the ice channel than on visibility when evaluating the probability of a ship besetting in ice. Conversely, when considering STIC probabilities, visibility takes on a greater level of significance than does the radius of the ice channel, according to the experts.
- The probability of the ITSC during breaking loose operation impacts the combined risk level. However, there is limited research on this topic, and further investigation is warranted.
- When visibility worsens, it could be challenging to follow the icebreaker's track. Under light ice conditions, the model shows that it is advisable to maintain an extended distance, with further extension warranted in cases of reduced visibility. In contrast, under severe ice conditions, it is recommended to maintain a short to medium distance during good visibility and not to decrease this distance when visibility worsens. This recommendation is provided based on three states for the distance estimate. Further research should focus on the discretization of the distance parameter into additional states and refining the model in cooperation with ship captains and meteorological and oceanographic services.

CRediT authorship contribution statement

Sheng Xu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ekaterina Kim:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Data curation.

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.

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Appendix A

Dear expert, greetings!

Escort/Convoy operations can efficiently assist ships in navigating polar regions. However, this navigation mode carries two risks: 1) ships colliding with icebreakers within ice channels and 2) ships becoming trapped within ice channels and colliding with icebreakers during icebreaking operations. We developed a Bayesian network model to assess the risk level of Arctic escort/convoy navigation. The model includes the probability and consequences of ship collisions with icebreakers, as well as the probability of ships becoming stuck in the ice channel and the severity of collisions with icebreakers during icebreaking operations. We have set up several navigation scenarios and kindly request your judgment based on your navigation experience. Your judgment will be compared with the model's output to validate its reliability.

This questionnaire is voluntary and will take approximately 15–20 min of time. We greatly appreciate your assistance in completing the survey. All your personal information will be kept strictly confidential throughout the entire research process.

Section 1 Background

1. What is your position onboard?
2. How long have you worked for this position?
3. How many years of ice navigation experience do you have?
4. Have you ever received training on polar navigation?

Section 2: Instructions for Completion

We employed a Bayesian network model to assess the risks of ship convoy navigation, including the probabilities of ship entrapment and ship collisions with icebreakers. The Bayesian network structure consists of three parts:

1) Nodes: These represent different risk factors, with the most fundamental risk factor referred to as the basic node. The risk factors are discretized into different states; for example, navigation experience can be discretized into three states (rich: experience >10 years, medium: 5 years ≤ experience ≤10 years, brief: experience < 5 years).
2) Arrows: These represent the causal relationships between risk factors.
3) Conditional probability table (CPT): This table is used to quantify the relationship between risk factors. In general, this CPT is determined based on data, expert judgment, or a combination of both.

For example, crew fitness is influenced by factors such as crew pressure, crew fatigue, navigation experience, and level of training. An example Bayesian model is shown in Fig. 1, and the whole model for estimating the probability of a ship besetting in ice and ship collision with the icebreaker is shown in Fig. 2. A description of the nodes in the model is shown in Table 1.

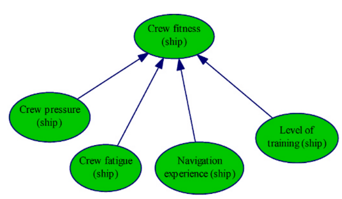

Fig. 1. The BN model for crew fitness (ship).

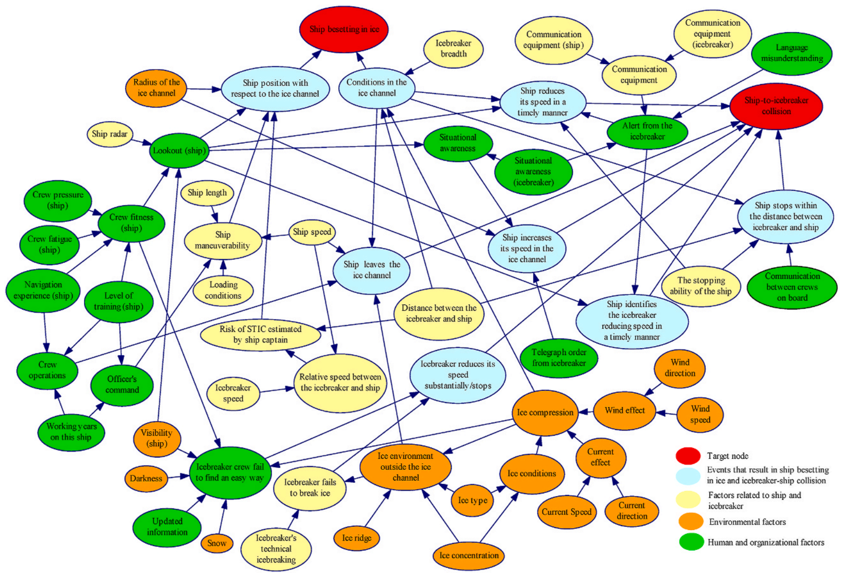

Fig. 2. BN for estimating the probability of a ship besetting in ice and a ship colliding with the icebreaker.

Table 1
Description of identified nodes for the developed model

Nodes	States	Description
Ship besetting in ice	No, yes	Related to the outcome node of the ship besetting in ice.
Ship-to-icebreaker collision	No, yes	Related to the outcome node of the ship colliding with the icebreaker.
Ship position with respect to the ice channel	In the channel, deviation from the channel	Refers to the ship position with respect to the ice channel.
Conditions in the ice channel	Open, partially closed, closed	Refers to the conditions of the ice channel. *Open* implies an open-water channel in ice field, cleaned of ice fragments; *partially closed* implies that the ice fragments move to the middle of ice channel, causing the open-water channel to narrow; *closed* implies that the ice channel is fully covered by ice fragments.
Radius of the ice channel	Sufficient, insufficient	*Sufficient* refers to the radius of the ice channel sufficing for the ship to change the heading direction alongside the ice channel.
Lookout (ship)	Sufficient, insufficient	Refers to the awareness of what is truly happening on the icebreaker and the ice channel and assesses the impact on the ship now and in the future. It is affected by ship radar, visibility, and crew fitness. *Sufficient* implies the on-duty crew always looks out for problems and can take action immediately. *Insufficient* implies that the on-duty crew could not determine the problem in time and results in delayed action.
Ship radar	Functioning, failed	Refers to the working state of the ship radar.
Visibility (ship)	Good, low	Refers to the distance at which the behavior of the icebreaker is discerned. *Good* implies that icebreaker's behavior can be clearly observed by the ship. *Low* implies the behavior of the icebreaker is vague or invisible to the ship.
Ship maneuverability	Normal, reduced	Refers to the maneuvering of a ship such as turning, course-keeping and stopping abilities of the ship.
Ship length	Long, medium, short	Refers to the length of the ship that is the object in the research. *Long:* length $>$200 m, *medium*: 120 $\leq$ length $\leq$200 m, *short*: length $<$ 120 m.
Loading conditions	Full load, light load	Refers to the loading condition of the ship.
Ship speed	High, medium, low	Refers to the speed of the ship. *High*: $>$8 kn, *medium*: 4 kn $\leq$ speed $\leq$8 kn, *low*: speed $<$ 4 kn.
Icebreaker speed	High, medium, low	Refers to the speed of the icebreaker. *High*: $>$8 kn, *medium*: 4 kn $\leq$ speed $\leq$8 kn, *low*: speed $<$ 4 kn.
Risk of STIC estimated by ship captain	High, low	Refers to the probability of the ship colliding with the icebreaker in the ice channel. The collision risk is dependent on the relative speed and distance between the icebreaker and assisted ship. *High:* probability $\geq$0.5, *low:* probability $<$ 0.5.
Distance between the icebreaker and the ship	Short, moderate, long	Refers to the distance between the bow of the assisted ship and the stern of the icebreaker. *Short:* distance $<$ 1/4 nm, *moderate:* 1/4 m $\leq$ distance $\leq$3/4 nm, *long:* distance $>$3/4 nm.
Relative speed between the icebreaker speed and the ship speed	Positive (more than 0.5 kn), neutral (between $-$0.5 kn and 0.5 kn), negative (less than $-$0.5 kn)	Refers to the relative speed between the icebreaker and ship along the ice channel. The relative speed is equal to the icebreaker speed minus ship speed. *Positive* implies that icebreaker speed is higher than the ship speed. *Neutral* implies the icebreaker and ship are almost equal. *Negative* implies the icebreaker speed is lower than the ship speed.
Officer's command	Suitable, unsuitable	Refers to the on-duty officer's operational command to ensure that the ship navigates normally. *Suitable* implies the operational order is suitable for the ship to perform, (e.g., the steering order is suitable for the ship to make a specific turn). This node is strongly dependent on the officer's working years on this ship and the officer's level of training.
Crew operation	Sufficient, insufficient	Refers to the quality of crew operating the ship.

(*continued on next page*)

Table 1 (*continued*)

Nodes	States	Description
Working years on this ship	High, medium, low	Refer to the familiarity of with the characteristics of equipment on board. *High*: working years >4 years, *medium*: 2 years $\leq$ working years ≤ 4 years, *low*: working years < 2 years.
Icebreaker crew fail to find an easy way	Yes, no	Refers to the icebreaker crew finding an easy way, for example ice lead, areas with light ice conditions, to ensure the icebreaker and the escorted ship to navigate successfully.
Darkness	Yes, no	Refers to the conditions of natural illumination.
Updated information	Yes, no	Refers to the state of the navigational information, such as ice chart, depth of water.
Snow	Significant, insignificant	Refers to the degree of snow covering the ice. *Significant* implies the snow cover is thick such that the crew cannot distinguish the ice thickness, ice type. *Insignificant* implies the snow cover does not affect the observation and judgment.
Icebreaker breadth	Large, medium, small	Refers to the breadth of the icebreakers in service in the Northeast Passage. *Large*: breadth $\geq$28 m, *medium*: 22 m $\leq$ breadth $<$ 28 m, *Small*: breadth $<$ 22 m.
Ice environment outside the ice channel	Severe, medium, light	It is calculated based on the ice compression, ice ridge, ice concentration, and ice type factors.
Ice type	Thick, moderate, light	Ice type is one parent node of ice conditions, which contains three states: thick, moderate, light. Thick: thickness of ice $\geq$120 cm, such as first-year thick ice, multiyear ice, moderate: 70 cm $\leq$ thickness of ice $\leq$120 cm, light: thickness of ice $<$ 70 cm.
Ice ridge	Yes, no	The ice concentration is the dominant factor in ice ridging. The frequently quoted threshold for ridging is 0.8. Yes: ice concentration $\geq$0.8, no: ice concentration $<$ 0.8.
Ice compression	High, medium, low	The ice compression is primarily caused by air forces (i.e., wind) and water forces (i.e., current), and wind forces dominate the ice drift. However, ice compression exists when the ice extends to the coastline. Ice compression can be divided into three states indicated by wind speed. High: wind force $>$8, medium: 4 $<$ wind force $\leq$8, low (or none): wind force $\leq$4.
Ice concentration	High, medium, low	Refers to the amount of ice in an given area and described as a percentage. High: concentration $>$70%, medium: 30% $\leq$ concentration $\leq$70%, low: concentration $<$ 30%.
Ice conditions	Heavy, medium, light	The ice conditions are adopted from the Northern Sea Route Administration, which contains three states. Heavy: the concentration of first-year thick ice $\geq$30%, medium: the concentration of first-year medium ice $>$30%, light: the concentration of first-year medium ice $\leq$30%.
Icebreaker fails to break ice	Yes, no	Refers to whether the icebreaker breaks the ice successfully. It is affected by the ice conditions around the icebreaker and the icebreaker's technical icebreaking capacity.
Icebreaker's technical icebreaking	High, medium, low	Refers to the icebreaking capacity of the icebreaker, which is indicated by ice thickness. *High*: ice thickness $\geq$2 m. *Medium*: 2 m $>$ ice thickness $\geq$1 m. *Light*: ice thickness $<$ 1 m.
Wind effect	Strong, medium, light	Refers to the effect of wind on the closing of the ice channel, which is dependent on the wind speed and wind direction relative to the ice channel.
Wind speed	Fast, moderate, slow	Refers to the velocity of the wind. The state of wind is described by the Beaufort scale, the relation between the Beaufort scale and wind speed can be found online. *Extreme*: Beaufort number 9–12 (velocity $\geq$20.8 m/s), *moderate*: Beaufort number 5–8 (8.0 m/s $\leq$ velocity $\leq$20.7 m/s), *calm*: Beaufort number 1–4 (velocity $\leq$7.9 m/s).
Wind direction	Perpendicular direction, parallel direction	Refers to the angle between the line of wind direction and the middle line of the ice channel. *Perpendicular direction*: $45^\circ \leq$ angle $\leq 90^\circ$, *horizontal direction*: $0^\circ \leq$ angle $< 45^\circ$
Current effect	Extreme, moderate, calm	Refers to the current effect on the closing of the ice channel, which is dependent on the wind speed and wind direction relative to the ice channel.
Current speed	High, low	Refers to the velocity of the current. *High*: speed $\geq$0.4 m/s, *low*: speed $<$ 0.4 m/s.
Current direction	Perpendicular direction, parallel direction	Refers to the angle between the line of current direction and the middle line of the ice channel. *Perpendicular direction*: $45^\circ \leq$ angle $\leq 90^\circ$, *horizontal direction*: $0^\circ \leq$ angle $< 45^\circ$.
Icebreaker reduces its speed substantially/stops	Yes, no	Refers to the icebreaker speed reduction. *Yes*: refers to the icebreaker speed reduces substantially, such as more than 5 kn, or even reduces to 0.
Ship increases speed in the ice channel	Yes, no	Refers to the ship speed increment. *Yes*: indicates the ship speed is reduced substantially, such as by more than 5 kn.
Ship leaves the ice channel	Yes, no	Refers to whether the ship leaves the ice channel successfully.
Telegraph order from the icebreaker	Suitable, unsuitable	Refers to the telegraph order from the icebreaker to ensure that the ship navigates effectively. Suitable implies the operational order is suitable for the ship to perform (e.g., the engine order is suitable for the ship to reduce the speed correctly).
Ship identifies the icebreaker reducing speed in a timely manner	Yes, no	Refers to the ship crew's ability to promptly identify whether the icebreaker is reducing speed or not in a timely manner.
Situational awareness	Enough, not enough	Refers to the ability to comprehend a given circumstance and gather relevant information. It involves the escort operation system (including the icebreaker and the escorted ship).
Situational awareness (icebreaker)	Enough, not enough	Refers to the icebreaker's ability to comprehend a given circumstance by gathering relevant information.
The ship reduces speed in a timely manner	Yes, no	Refers to the ship's prompt reduction in speed to avoid colliding with the icebreaker
Communication between crews on board	Effective, ineffective	Refers to the communication efficiency between the crews on the assisted ship. 'Effective' implies that cooperative actions are clearly understood. 'Ineffective' implies that cooperative actions are difficult to understand, which is caused by language, noise, etc.
Stopping ability of the ship	Strong, medium, low	The ship's stopping ability is primarily affected by engine power, speed, and draft. In this paper, the stopping ability of the ship is indicated by its speed. Low: $>$8 kn, medium: 4 kn $\leq$ speed $\leq$8 kn, strong: speed $<$ 4 kn.
Ship stops within the distance between icebreaker and ship	Successful, failed	Refers to the ship stopping within the distance between the icebreaker and ship.
Alert from the icebreaker	Timely, not timely	Refers to whether the icebreaker provides a timely alert when emergencies occur.
Language misunderstanding	Yes, no	Refers to the understanding of the calling from the icebreaker.

(*continued on next page*)

Table 1 (*continued*)

Nodes	States	Description
Communication equipment	Functioning, failed	Refers to the state of the communication equipment (VHF). *Functioning* implies both the icebreaker and the ship VHF are functioning, *failed* refers to failure of VHF on the icebreaker and/or ship.
Communication equipment (ship)	Functioning, failed	Refers to the state of the communication equipment (VHF). *Functioning* implies the ship VHF is functioning, *failed* refers to failure of VHF on the ship.
Communication equipment (icebreaker)	Functioning, failed	Same as 'communication equipment (ship)'.
Crew fitness (ship)	High, moderate, low	Refers to the state of the ability of the crew to conduct the work onboard, which is affected by crew fatigue, crew pressure, navigation experience, and level of training.
Crew fatigue (ship)	Severe, moderate, light	Refers to the working hours after the crew took over. *Severe*: working hours >2.6 h, *moderate*: 1.3 h ≤ working hours ≤2.6 h, *light:* working hours < 1.3 h.
Level of training (ship)	Extra, basic	Refers to the crew training. *Basic* implies the crew on board has completed the training needed by Polar Code and International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), this is the minimum requirement of training for crew shipping in the Arctic. *Extra* refers to additional training conducted by the ship company or other qualified institutions for a specific area, specific voyage, etc.
Navigation experience (ship)	Rich, medium, brief	Refers to the working experience in Arctic areas. *Rich*: experience >10 years, *medium*: 5 years ≤ experience ≤10 years, *brief*: experience < 5 years.
Crew pressure (ship)	High, moderate, low	Refers to the mental pressure that results mainly from whether the crew is familiar with the mode of operation (convoy operation) and whether the crew can adjust to the working environment (e.g., noise and vibrations caused by the ship hitting ice). *High* implies that the crew is not familiar with the mode of operation and cannot adjust to the working environment. *Moderate* implies that the crew is not familiar with the mode of operation or working environment. *Low* implies that the crew is familiar with the mode of operation and can adjust to the working environment.

Section 3: Scenario estimation

To validate the model output, we designed several scenarios that rely on the input of the basic nodes. The model has 31 basic nodes in total, and 23 basic nodes (marked by red in Table 2) maintain the same state in all scenarios. The other 8 basic nodes change their states in different scenarios. For each scenario, please give your estimated probability of a ship besetting in ice and ship-to-icebreaker collision. Please note that a probability equal to or less than 30% is regarded as "Low", a probability between 30% and 70% is regarded as "Medium", and a probability equal to or greater than 70% is regarded as "High".

Table 2
The designed scenarios

<table>
<tr><th>Scenario</th><th>Basic node</th><th>State</th><th colspan="2">Description</th></tr>
<tr><td rowspan="17">These basic nodes will keep the same states in all scenarios</td><td>Icebreaker’s technical icebreaking</td><td>High</td><td colspan="2">Break ice thickness > 2 m</td></tr>
<tr><td>Icebreaker breadth</td><td>Large</td><td colspan="2">Breadth ≥ 28 m</td></tr>
<tr><td>Communication equipment (icebreaker)</td><td>Functioning</td><td colspan="2"></td></tr>
<tr><td>Telegraph order from the icebreaker</td><td>Suitable</td><td colspan="2"></td></tr>
<tr><td>Situational awareness (icebreaker)</td><td>Enough</td><td colspan="2"></td></tr>
<tr><td>Ship length</td><td>medium</td><td colspan="2">Medium: 120 ≤ length ≤ 200 m</td></tr>
<tr><td>Ship loading conditions</td><td>Full loaded</td><td colspan="2"></td></tr>
<tr><td>The stopping ability of the ship</td><td>Strong</td><td colspan="2"></td></tr>
<tr><td>Ship radar</td><td>Functioning</td><td colspan="2"></td></tr>
<tr><td>Communication equipment (ship)</td><td>Functioning</td><td colspan="2"></td></tr>
<tr><td>Level of training (ship)</td><td>Extra</td><td colspan="2"></td></tr>
<tr><td>Crew working years on this ship</td><td>High</td><td colspan="2"></td></tr>
<tr><td>Crew fatigue (ship)</td><td>light</td><td colspan="2"></td></tr>
<tr><td>Crew pressure (ship)</td><td>low</td><td colspan="2"></td></tr>
<tr><td>Communication between crews on board</td><td>Effective</td><td colspan="2"></td></tr>
<tr><td>Language misunderstanding between icebreaker and ship</td><td>No</td><td colspan="2"></td></tr>
<tr><td>Updated information (Meteorological conditions, etc.)</td><td>Yes</td><td colspan="2"></td></tr>
<tr><td rowspan="6"></td><td>Snow</td><td>Insignificant</td><td colspan="2"></td></tr>
<tr><td>Darkness</td><td>No</td><td colspan="2"></td></tr>
<tr><td>Wind Speed</td><td>Slow</td><td colspan="2">Speed ≤ 7.9 m/s</td></tr>
<tr><td>Wind direction</td><td>Parallel direction</td><td colspan="2"></td></tr>
<tr><td>Current Speed</td><td>Low</td><td colspan="2">Speed < 0.4 m/s</td></tr>
<tr><td>Current direction</td><td>Parallel direction</td><td colspan="2"></td></tr>
<tr><td rowspan="10">Scenarios 1-4</td><td>Icebreaker speed</td><td>Medium</td><td colspan="2">Medium: 4 kn ≤ speed ≤ 8 kn</td></tr>
<tr><td>Ship speed</td><td>Medium</td><td colspan="2">Medium: 4 kn ≤ speed ≤ 8 kn</td></tr>
<tr><td>Distance between the icebreaker and the ship</td><td>Medium</td><td colspan="2">Medium: 1/4 nm ≤ distance ≤ 3/4 nm</td></tr>
<tr><td>Visibility (ship)</td><td>Good</td><td colspan="2"></td></tr>
<tr><td>Radius of the ice channel</td><td>Sufficient</td><td colspan="2"></td></tr>
<tr><td>Navigation experience (ship)</td><td>Rich</td><td colspan="2">Rich: experience >10 years</td></tr>
<tr><td>Scenario 1</td><td>Scenario 2</td><td>Scenario 3</td><td>Scenario 4</td></tr>
<tr><td>Ice type: 70 cm ≤ thickness of ice ≤ 120 cm</td><td>Ice type: thickness of ice ≥ 120 cm</td><td>Ice type: thickness of ice < 70 cm</td><td>Ice type: thickness of ice < 70 cm</td></tr>
<tr><td>Ice ridge: No</td><td>Ice ridge: Yes</td><td>Ice ridge: No</td><td>Ice ridge: Yes</td></tr>
<tr><td>Ice concentration: 30% ≤ concentration ≤ 70%</td><td>Ice concentration: concentration > 70%</td><td>Ice concentration: concentration < 30%</td><td>Ice concentration: concentration > 70%</td></tr>
<tr><td rowspan="10">Scenarios 5-7</td><td>Icebreaker speed</td><td>Medium</td><td colspan="2">Medium: 4 kn ≤ speed ≤ 8 kn</td></tr>
<tr><td>Ship speed</td><td>Medium</td><td colspan="2">Medium: 4 kn ≤ speed ≤ 8 kn</td></tr>
<tr><td>Distance between the icebreaker and the ship</td><td>Medium</td><td colspan="2">1/4 nm ≤ distance ≤ 3/4 nm</td></tr>
<tr><td>Ice type</td><td>Medium</td><td colspan="2">70 cm ≤ thick of ice ≤ 120 cm</td></tr>
<tr><td>Ice ridge</td><td>No</td><td colspan="2"></td></tr>
<tr><td>Ice concentration</td><td>Medium</td><td colspan="2">30% ≤ concentration ≤ 70%</td></tr>
<tr><td>Navigation experience (ship)</td><td>Rich</td><td colspan="2">Rich: experience >10 years</td></tr>
<tr><td>Scenario 5</td><td>Scenario 6</td><td colspan="2">Scenario 7</td></tr>
<tr><td>Visibility (ship): Good</td><td>Visibility (ship): Low</td><td colspan="2">Visibility (ship): Low</td></tr>
<tr><td>Radius of the ice channel: Insufficient</td><td>Radius of the ice channel:</td><td colspan="2">Radius of the ice channel: Insufficient</td></tr>
</table>

		Sufficient		
Scenarios 8-10	Icebreaker speed	Medium	Medium: 4 kn ≤ speed ≤ 8 kn	
	Ship speed	Medium	Medium: 4 kn ≤ speed ≤ 8 kn	
	Distance between the icebreaker and the ship	Medium	1/4 nm ≤ distance ≤ 3/4 nm	
	Ice type	Medium	70 cm ≤ thick of ice ≤ 120 cm	
	Ice ridge	No		
	Ice concentration	Medium	30% ≤ concentration ≤ 70%	
	Radius of the ice channel	Sufficient		
	Scenario 8	**Scenario 9**	**Scenario 10**	
	Visibility (ship): Good	Visibility (ship): Low	Visibility (ship): Low	
	Navigation experience (ship): less than five years	Navigation experience (ship): more than 10 years	Navigation experience (ship): less than five years	
Scenarios 11-14	Icebreaker speed	Medium	Medium: 4 kn ≤ speed ≤ 8 kn	
	Ship speed	Medium	Medium: 4 kn ≤ speed ≤ 8 kn	
	Ice type	Medium	70 cm ≤ thick of ice ≤ 120 cm	
	Ice ridge	No		
	Ice concentration	Medium	30% ≤ concentration ≤ 70%	
	Radius of the ice channel	Sufficient		
	Navigation experience	Rich	Rich: experience >10 years	
	Scenario 11	**Scenario 12**	**Scenario 13**	**Scenario 14**
	Visibility (ship): Good	Visibility (ship): Low	Visibility (ship): Low	Visibility (ship): good
	Distance: distance < 1/4 nm	Distance: distance < 1/4 nm	Distance: distance > 3/4 nm	Distance: distance > 3/4 nm
Comments	**Do you have any comments on the model and estimation of the probability?**			

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