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Published in:
Reliability Engineering and System Safety

DOI:
10.1016/j.ress.2022.108475

Published: 01/07/2022

Reliability Engineering and System Safety 223 (2022) 108475

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

A Bayesian network risk model for predicting ship besetting in ice during convoy operations along the Northern Sea Route

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ARTICLE INFO

Keywords:
Ship besetting in ice
Convoy operations
Northern Sea Route
Bayesian Network
Maritime safety

ABSTRACT

To facilitate shipping in ice and to meet the increasing requirements of icebreaker services, convoy operations are the most effective alternative. However, convoy operations are among the most dangerous operations as they can result in ship-ship collisions and/or ship besetting in ice. To safeguard the assisted ships and improve the efficiency of convoy operations, predicting the besetment event is a paramount proactive measure. In this study, a Bayesian Network model is developed to predict the probability of ship besetting in ice in a convoy operation along the Northern Sea Route (NSR). The model focuses on the first-assisted ship and is based on expert elicitation. Correspondingly, four scenarios that may result in the first assisted ship besetting in ice have been identified. Further, the applicability of the model is evaluated through 12 scenarios derived from the real NSR voyage of 'TIAN YOU' assisted by the icebreaker 'VAYGACH' in August 2018. The results of the model evaluation and validity studies indicate that the developed model is feasible and can adequately predict the besetment event of the first assisted ship in convoy operations. The most important factors contributing to besetting in ice were found to be ice concentration, distance between icebreaker and ship, and navigation experience.

1. Introduction

With global warming, the sea ice extent in the Arctic has been on the decline in recent years, resulting in an increase in ship traffic in the Arctic. Over the past six years, the traffic volume on the Northern Sea Route (NSR) has grown eightfold [1]. The interest in using NSR has grown even more following the blocking of the Suez Canal for six days caused by the accidental grounding of Ever Given [2]. Moreover, Russia has initiated a project, aiming to increase cargo traffic to 80 million tons by 2024, compared to 33 million tons as of 2020 [3]. All these facts indicate that marine transportation in the Arctic could significantly increase. However, uncertain ice conditions, harsh environments, and lack of infrastructure are still major obstacles that hinder shipping along the NSR. To facilitate ships navigating in severe ice conditions and to satisfy the demand for icebreaker services for the rapid growth of traffic volume, convoy operations appear to be the best and most efficient alternative [4,5]. Based on operational experience, navigation under icebreaker assistance can be classified into four identified icebreaker operations: (1) escort operations, (2) convoy operations, (3) breaking ship loose operations, and (4) towing operations [6–8]. A convoy operation in ice-covered waters is defined as 'the operation when an icebreaker creates an ice channel, followed by several assisted ships at a recommended distance and/or speed and/or mode of the main engine' [6,7,9].

Compared to open water transits, the probability of accidental events (e.g., ship-ship and/or ship-ice collisions, grounding) under icebreaker assistance is regarded as considerable and higher [10–12]. In addition, the increasing traffic volume also requires increased crews with experience of operating ships in ice-covered waters and more organizational management. However, human factors such as lack of navigation experience in the Arctic (e.g., NSR), insufficient level of training, and high crew pressure may increase the shipping risk in a convoy operation. Consequently, organizational factors such as the provision of a suitable Planned Maintenance System (PMS) for critical equipment (e.g., main engine, steering gear, and auxiliary diesel generators) and the PMS training to onboard personnel can promise the normal conditions of equipment during navigation in the Arctic.

A hazardous event in a convoy operation is ship besetting in ice. Once the front ship besets in ice, it could result in serious ship-ship/ship-ice collisions, resulting in damage to the ship structure, environmental pollution, and jeopardising the safety of the crew [8]. At the mercy of ice, wind, wave, and current, the beset ship carries a high risk of

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https://doi.org/10.1016/j.ress.2022.108475
Received 16 November 2021; Received in revised form 15 February 2022; Accepted 15 March 2022
Available online 21 March 2022

grounding and hull damage. In addition, besetment may also lead to severe disruption of a vessel's transit schedule [13].

Contributing to risk management during navigating in ice, this paper presents a Bayesian Network (BN) model for assessing the probability of the ship besetting in ice during a convoy operation. The model focuses on the first-assisted ship in a convoy operation. The following issues were considered:

1) The scenarios that result in ship besetment in a convoy operation;
2) The corresponding risk factors; and
3) Feasibility of the model.

The structure of this paper is organised to address these issues. Section 2 presents a BN model for predicting the probability of a ship besetment. Section 3 describes the case study used to demonstrate the feasibility of the developed model. In Section 4, an additional model validity study is presented. Finally, Sections 5 and 6 provide a discussion and concluding remarks, respectively.

2. Relevant studies on ship besetting in ice

The literature reviewed in this section is dedicated to studying ship besetting in ice. Several studies have already focused on the impact of ice pressure on ship besetting in ice. Kubat [14] obtained significant risk factors that result in ice pressure by distributing a questionnaire to captains who operated ships through Canadian waters. Based on the surveyed results, Kubat [15] further developed besetment criteria in terms of ice pressure and ridge height by examining two separate ship besetment events in the Gulf of St. Lawrence in March 2005. Subsequently, this criterion was applied to analyse the besetment events in Frobisher Bay during the 2012 shipping season [16], the Gulf of St. Lawrence and the Strait of Belle Isle during the winters of 2013 and 2014 [17], and Beaufort Sea [18]. Similar research was conducted by [13] in which the parameters included ice concentration, ice thickness, ice floe size, distance from the nearest coastline, wind (i.e., wind speed and wind direction), and current. However, the aforementioned studies were tailored for a particular vessel type and power, and only the explicit risk factors related to ice pressure were considered.

Collecting besetment events and studying the patterns behind them is an effective alternative. Mussells [19] examined the relationship between besetment events and ridge densities based on the collected 33 besetment events endured by the vessel MV Arctic in the Hudson Strait between 2005 and 2014. Vanhatalo [20] proposed a hierarchical Bayesian approach to predict the probability of a besetting event by integrating 58 historical besetting events with AIS data, ice data. However, this kind of research is largely dependent on the quantity and quality of collected data. Thus, the deficiency of collected data may lead to different results.

A few recent research have focused on probabilistic models for predicting ship besting in ice. Fu [21] developed a BN containing nine risk factors to predict the probability of ship besetting in ice along the NSR. This study focused on an escort operation. Zhang [22] developed a BN to analyse ship besetting in ice and ship-ice collision for an independent ship navigating in the Arctic. Montewka [23] developed two BNs to predict the performance of a ship in an ice field. One BN model was applied to analyse the joint effect of ice conditions on a ship's speed, while the other was used to predict the probability of ship besetting in ice. The analysed voyage was a mix of independent navigation and escort operations. Li [24] built a BN to predict the probability of ship speed under given ice conditions and the model was utilised with a large set of full-scale data. Although it doesn't directly analyse the ship besetment, it has application potential in the risk analysis of besetting in ice.

Rather of addressing the causes of ship besetting in ice, the studies of ship performance and operability simulation provide an indirect technique to estimate the ship besetting in ice. For example, Kuuliala [25] used a transit simulation-based approach to estimate the distribution of mean ship speeds and the probability of ship besetting in ice in ridged ice conditions. Su [26] used a numerical method to simulate ship maneuvers in level ice. Li [27] investigated the ship performance in the ice channel that is narrower than the beam of assisted ship. Lu [28] developed a transit model to assess the operability of ship in dynamic ice conditions. Huang [29] simulated the ship operating in an open-water ice channel.

As a result, there are presently no models that focus on the ship besetting in ice during convoy operations along the NSR. For shipping in the NSR, where convoy operations will be the most efficient alternative [4,5], it is critical to comprehensively understand the risk factors that cause ship besetting in ice and precisely estimate the probability of ship besetting in ice. The risk factors considered in the key reviewed literature are summarised in Table 1. The detailed ice-related risk factors (e.g., level ice thickness, ridge concentration, ridge thickness) in each literature are described by the term 'ice conditions' in Table 1. The studies that relate to ship besetting in ice till date have not considered human and organizational risk factors. However, in practice, these factors have a considerable contribution to maritime accidents [30–33]. Moreover, the harsh environment (e.g., low temperature, difficult ice conditions, darkness most of the year) in the Arctic may also considerably influence the decision-making and crew operation [34,35].

This study tries to fill these knowledge gaps and the originality of this work is characterized as below:

1) to the best of the authors' knowledge, it is the first probabilistic model to estimate the ship besetting in ice in convoy operations and focusing on NSR specifics;
2) the model considers human and organizational factors; and
3) the model considers significant practical factors highlighted in the captain consultation, such as relative distance between icebreaker and ship, ice conditions in the ice channel, etc., that earlier models did not cover.

3. Bayesian Network development for ship besetting in ice during convoy operations

3.1. Bayesian Network

A BN belongs to the family of graphical models and is a directed acyclic graph. This represents the causal dependency between the variables by arcs/lines. It comprises three elements:

Element 1 - node, which indicates the variables;
Element 2 - node directed arcs/line with arrows, which demonstrates the causation relationship between nodes;
Element 3 - Conditional Probability Table (CPT), which contains the conditional probability of each state of the nodes, to quantify the causation relationship.

Table 1
Risk factors collected from the key reviewed literature.

Risk factors	References
Ice compression	[14-18,23]
Ship power	[14,21,24]
Ship speed	[14,21- 23,25]
Wind	[13,15-18,21-23]
Current	[15–18]
Ice conditions	[13,15–25]
Wave	[13,21,22]
Distance from coastline	[17]
Air and sea temperature	[21]
Visibility	[21]
Ice class	[20]

BN can express combinations of complex system variables, incorporate new observations, and interpret inherent causation factors and their associated probabilities of occurrence. Further details regarding BNs can be found in the studies by Jensen [36] and Langseth [37]. BNs have been extensively used in maritime domains, including Arctic shipping. In ice-free waters, this model has been applied in various accident scenarios, such as collision [38–44], grounding [45–47], fire and exploration [48–51], and for different ship types [52–54]. Whereas, in ice-covered waters, the BN models have been reviewed in our previous study [9] and they cover scenarios such as ship collisions [55,56], ship-ice collisions [57–60], and besetting in ice [21,23,24]. Furthermore, this model is well suited to model uncertainty in a domain or system considering human and organizational factors [61–63].

3.2. BN for ship besetting in ice in convoy operations

This section elaborates on the process of developing the BN model for predicting the first-assisted ship besetting in ice during convoy operations, as shown in Fig. 1.

3.2.1. Identify the nodes (Element 1)

3.2.1.1. Target node of the model. The proposed model is used to predict the probability of ship besetting in ice. It was developed for the first assisted ship behind the icebreaker in a convoy operation, as shown in Fig. 2. Convoy operation was led by one icebreaker. The target node in the model is described as 'ship besetting in ice'.

3.2.1.2. Nodes. Node identification was performed based on literature review and scenario-based analysis with a subsequent verification by an expert (ship's Captain). A detailed description is provided below.

1) Scenario-based analysis with subsequent expert verification

Four scenarios that resulted in the first assisted ship besetting in ice were identified:

i. A loss of propulsion power and/or steering that directly causes ship besetting in ice;
ii. A Loss of propulsion power and/or steering on the icebreaker, which causes ship besetting in ice;
iii. The ship leaves the ice channel;
iv. The ice channel closes.

2) Node identification from a literature review with subsequent expert verification

The risk factors identified from the literature, as shown in Table 1, provide certain input references to the proposed model. Additional nodes were identified through iterative discussions, including those with a Captain who had served in the seas for nine years and with ice navigation experience in the Arctic.

After identifying the nodes, the nodes were discretized using two criteria:

- Minimize the number of states to three owing to the data requirements and to avoid the CPT increase exponentially with the number of states [64].
- The states were defined as binary states (e.g., 'ship besetting in ice') or as numerical values (e.g., the states of crew fatigue were based on the working hours after the crew took over). With regards to the states specified numerically, the underlying idea is that each state has the same/similar numerical duration. Consider the case of 'crew fatigue'. This variable was discretized into three states (i.e., severe, moderate, and light), and the officer's shift is four hours. Therefore, one-third of the shift (1.3 hours) is utilized to determine the numerical duration.

The identified nodes and the corresponding states are listed in Table A1 in Appendix A.

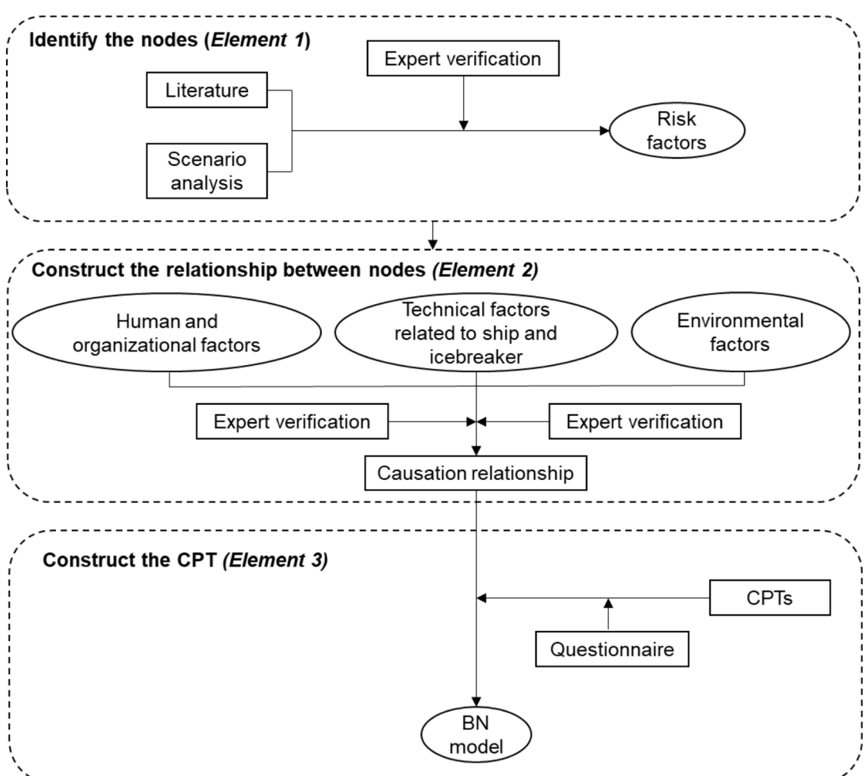

Fig. 1. BN development framework for ship besetting in ice in convoy operations.

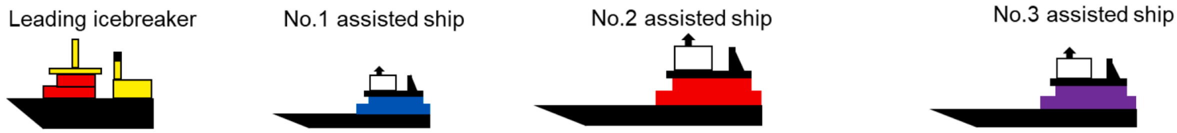

Fig. 2. Illustration of a convoy operation led by one icebreaker.

3.2.2. *Construct the relationship between nodes (Element 2)*

In the initial version of the BN model, certain causal relationships were assumed. However, numerous edits to the structure were made for each iteration of the proposed BN, and expert consultation was conducted to verify the relationships. Fig. 3 shows the relationship between nodes in the proposed BN model. Consider the 'look out (ship)' as an example, it has three parent nodes 'ship radar', 'visibility (ship)' and 'crew fitness (ship)'. This is based on the logic that: 1) If the 'ship radar' fails, the function of detecting the icebreaker's speed and position is lost, resulting in the inadequacy of the lookout; 2) Low visibility impedes observation of the ice conditions in the ice channel and icebreaker's behaviors, resulting in the lookout being insufficient; 3) Low crew fitness has a direct effect on the competence of lookout.

3.2.3. *Construct the CPT (Element 3)*

In this step, the relationships between nodes (i.e., CPT) were quantified. Theoretically, the formulation of CPT is achieved using historically recorded data, expert estimation, or a combination of both [65]. The common methods applied to building CPTs using partial expert information were summarised by Mkrtchyan [66]. We adopted the Røed method [67] with certain modifications (refer to the fourth step below), although other methods exist as well [68–71].

Method assumption: The probability assigned for a child node being in a state that differs considerably from its parents' states must be small compared to a state equal to or close to its parents' states. The greater the deviation between the parent node states and the state of the child node in focus, the smaller the probability that should be assigned [67].

Step 1 Distance between one parent node and child node: This is the distance of state between one parent node and child node. The distance is calculated using Eq. (1), where D is the distance between the state of the parent node and that of the child node. For example, for parent state 3 and child state 1, the distance was 2.

$$D = \left| State_{child} - State_{parent} \right| \tag{1}$$

Step 2 Weighted distance: Weights are designated by assessing the influence of the parent nodes on the child node. Following the determination of the weights of the parent nodes, the weighted distance is calculated using Eq. (2), where D_j is the distance between *jth* state of the child node and the states of all parent nodes, W_i is the weight of *ith* parent node, D_{ij} is the distance between *jth* state of the child node and the state of *ith* parent node, S_1 is the *1st* state of the child node, and S_n is the *nth* state of the child node.

$$D_j = \sum_{i=1}^{n} D_{ij} * W_i \ where \ j \in [S_1, \ S_n] \tag{2}$$

Step 3 Probability distribution: Equation (3) represents the formula to calculate the probability distribution of the states of the child node in focus, where the numerator term is the probability mass for *jth* state, and the denominator term provides a normalisation factor that makes the $P_j's$ sum up to 1. Further, the term R is an index value that determines the extent of the lower probability to be assigned for a high D_j compared to a low D_j. The higher the R index, the lower the probability that the child node is in a state distant from its parents' state. The value of R was determined by the experts.

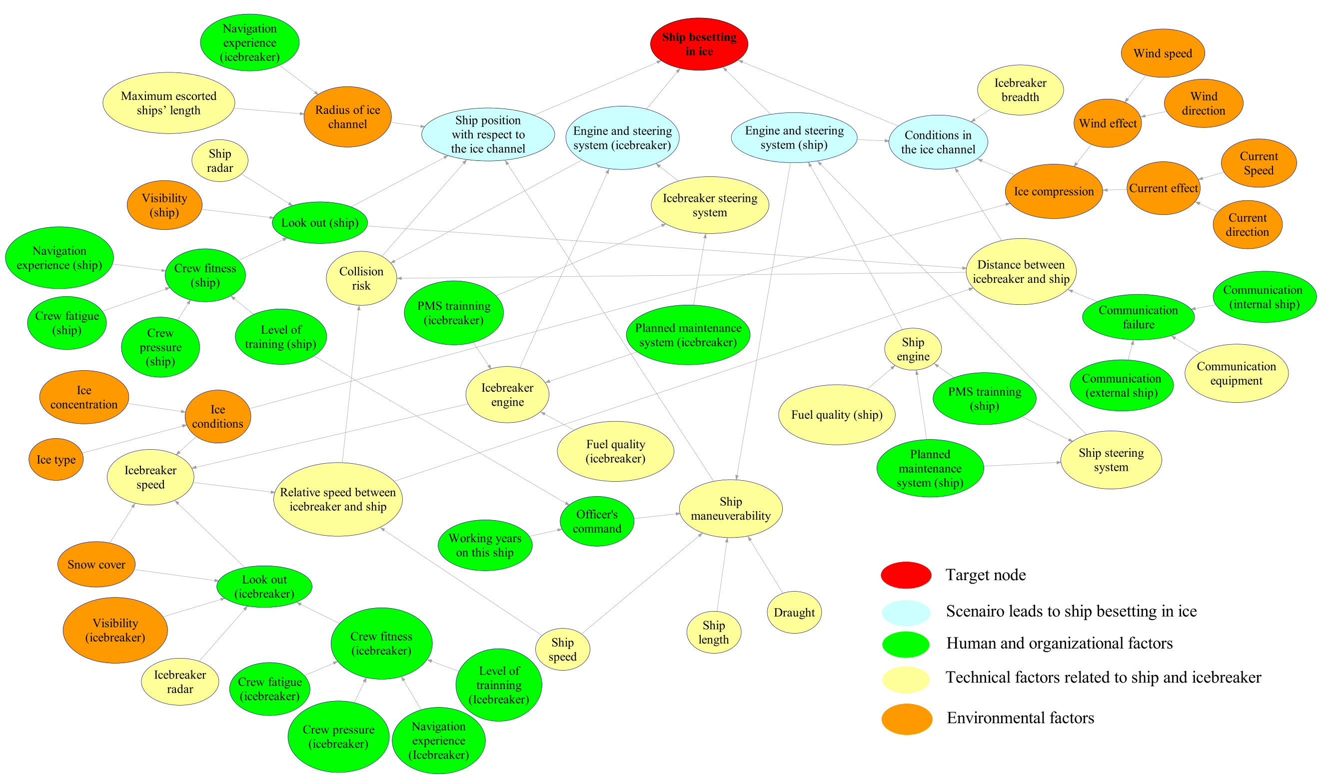

Fig. 3. Proposed BN for ship besetting in ice in convoy operations.

$$P_j = \frac{e^{-R*D_j}}{\sum_{S_1}^{S_n} e^{-R*D_j}} \text{ where } P_j \in [0,\ 1] \quad (3)$$

Step 4 Expert elicitation: The weights of the parent nodes and R index were estimated by experts. Thus, a questionnaire was designed and distributed to the domain experts. we received five feedbacks, and the backgrounds of the experts are shown in Table 2. The questionnaire split the entire model into 20 sub-models. For each sub-model, the Analytic Hierarchy Process (AHP) [72] was used to quantify the weights of the parent nodes, and a linear scale ranging from 0 to 10 was applied for the five experts to estimate the R index. The final weight of each parent node and the final R index is the average weight and average R based on the input of five experts, respectively. However, the CPT for node 'relative speed between icebreaker and ship' was determined differently. The reason along with the results are provided in Appendix B.

4. Case study

This section describes actual cases of ship besetting in ice events that were used to check the feasibility of the model. The besetment events occurred during August 2018 while navigating along the NSR. Details of the events and vessels involved are presented in the following sections. In addition to the crew, two academic researchers and two officers from the China Maritime Safety Administration were also on board to collect navigational information. The data used in this section were derived from the Automatic Identification System (AIS) data, the ship's logbook, and the voyage summary report. The AIS data were obtained from Shipfinder [73], and the other two data sources were supplied by the COSCO SHIPPING Specialized Carriers Co., Ltd. Appendix C presents the detailed information from the above resources.

4.1. The details of ships in the convoy operation

Four ships were involved in this convoy operation, and the details of each ship are listed in Table 3.

4.2. Description of the convoy operation

The convoy operation was led by the icebreaker 'VAYGACH'. The trajectory of the convoy operation is plotted in Fig. 4 based on the 'TIAN YOU' data obtained from the AIS. The details of this convoy operation are as follows.

1) This convoy operation started at 1830 UTC on 2 August 2018 at 68°30.5′ N, 176°59.6′W (WGS84). The type of fleet was 1+2, that is icebreaker 'VAYGACH' + the assisted ships: 'TIAN YOU' and 'YAROSLAV MUDRYY'
2) At 0130 UTC on 3 August 2018, position 69°11′ N, 179°32′ W, the ship 'CHUKOTKA+' joined this convoy operation, as shown in Fig. 5.
3) At 0300 UTC on 4 August 2018, position 72°23′ N, 170°37′ E, the 'VAYGACH' escorted the ship 'YAROSLAV MUDRYY' to port PEVEK.
4) At 0600 UTC on 4 August 2018, position 70°23.1′ N, 170°12.4′ E, the convoy operation was resumed. The type of fleet was 1+2, that is, 'VAYGACH' + 'TIAN YOU' and 'CHUKOTKA+'.

Table 2
Information related to the experts.

Experts	Position on board	Ice navigation experience/years	Academic research
E1	No	No	The navigation strategy of the fleet in the Arctic
E2	Chief officer	5	Navigation risk
E3	Captain	7	No
E4	Captain	10	Ship manoeuvrability in ice, ice loads on ship hulls
E5	Captain	9	No

Table 3
The details of ship information in the convoy operation.

Position in convoy	Leading Icebreaker	NO. 1	NO. 2	NO. 3
Ship name	VAYGACH	TIAN YOU	YAROSLAV MUDRYY	CHUKOTKA+
Ice class	RMRS LL2	FS Ice Class 1A	FS Ice Class 1A	FS Ice Class 1A
Length	149.7 m	189.99 m	123.72 m	140.8 m
Ship's width	28 m	28.50 m	18 m	21.2 m
Depth	15.68 m	15.80 m	10.6 m	10.7 m
Draught	9 m	11.00 m	8.36 m	7.314 m
Maximum speed	18.5 kn	14.80 kn	12.5 kn	14 kn
Construction year	1990	2017-2018	1993	1982

RMRS Ice Class: Russian Maritime Register of Shipping Ice Class.
FS Ice Class: Finnish-Swedish Ice Class.

5) At 0800 UTC on 7 August 2018, the convoy operation ended at 75°47′ N, 149°58.8′ E.

4.3. The application of the proposed model

To apply the proposed model, 12 scenarios (including besetting in ice) containing sufficient information for populating the developed model were identified from the logbook. Information, such as ice conditions, hydrometeorology, ship speed, ship position, etc., were recorded by the crew onboard. The exact times of the 12 scenarios and the on-duty senior officer of 'TIAN YOU' are shown in Table 4.

4.3.1. The basic nodes for the case study

The basic nodes for the case study were classified into three groups: Human and organizational factors (yellow clustered nodes in Fig. 3), technical factors related to ships and icebreaker (green clustered nodes in Fig. 3), and environmental factors such as weather and hydrological conditions (blue clustered nodes in Fig. 3).

4.3.1.3. Human and organizational factors. The icebreaker 'VAYGACH' has served in the Arctic for 30 years, and in this case study, we assumed that the state of 'navigation experience (on the icebreaker)' was 'rich' in all 12 scenarios. Other assumed human and organizational factors in which the states are not variable in the 12 scenarios are listed in Table 6.

The states of the remaining human factors vary among on-duty senior officers. The senior officers' information was collected from the voyage summary report, shown in Table 5, and the states of these basic nodes in the 12 scenarios are shown in Table 6.

4.3.1.4. Technical factors related to ships and icebreaker. The technical factors related to ship and icebreaker include static factors (e.g., ship length, ship engine, etc.) and dynamic factors (e.g., ship speed and relative distance between icebreaker and ship).

The static factors related to the ship and icebreaker were constant in all 12 scenarios. The failure probability of a ship engine varies depending on different sources, for example, 2.6×10^{-4} in [74], 2.04×10^{-4}, $5.30 \times ^{-4}$ in [60]. These failure probabilities mainly refer to ships that navigate in ice-free waters. However, considering the low temperature and frequently changing speed and course in convoy operations, the failure probability of the ship/icebreaker engine was assumed to be 1×10^{-3}. The failure probability assumed and the states of the other static factors are presented in Table 6.

The dynamic ship factors vary depending on the scenario. The detailed states of each scenario are shown in Table 7.

4.3.1.5. Environmental factors. Environmental factors were collected from the logbook, see Table C2 in Appendix C. For each scenario, the states of the environmental factors are listed in Table 7.

Fig. 4. The trajectory of the convoy operation (S1, S3. – Scenario 1, Scenario 3).

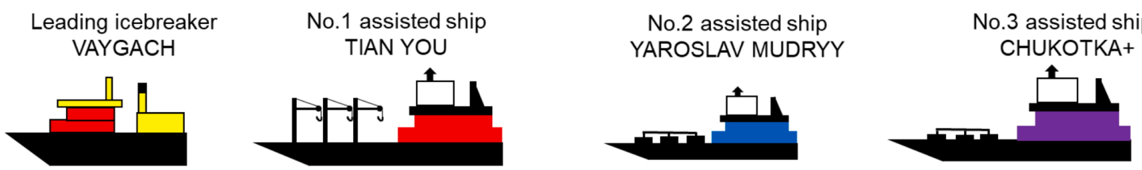

Fig. 5. The ship order in the convoy operation.

Table 4
Exact time and on-duty senior officer for 12 selected scenarios.

No.	Time (UTC)	On duty senior officer of 'TIAN YOU'
1	0130, 3 August	The second officer
2	0810, 3 August	The third officer
3	1230, 3 August	Chief officer
4	2130, 3 August	The third officer
5	1600, 4 August	Chief officer
6	2000, 4 August	The third officer
7	0500, 5 August	Chief officer
8	1015, 5 August	The third officer
9	1315, 5 August	The second officer
10	0300, 6 August	The second officer
11	1030, 6 August	The third officer
12	1500, 6 August	Chief officer

Table 5
The input state of human factors of senior officers on 'TIAN YOU'.

Basic node	Chief officer	Second officer	Third officer
Navigation experience	Medium	Medium	Brief
Crew pressure	Low	Low	Moderate
Level of training	Extra	Extra	Basic
Working years on this ship	Low	Low	Low

4.3.2. Construction of CPT

Based on the method introduced in Section 3.2.3, the procedures for calculating the CPTs have been elaborated in this section.

4.3.2.1. Create a questionnaire. A questionnaire was created to elicit expert opinions on the weights of parent nodes and R index of each sub-model, see Appendix D. The questionnaire was divided into three sections. The first section covers questions on the experts' backgrounds. Section 2 provides the AHP approach for estimating the weight of the parent node and the linear scale to estimate the value of R. Additionally, this section includes a sub-model that demonstrates how to complete the questionnaire. Section 3 subdivides the BN model into 20 submodels. Experts were requested to respond to pre-designed questions in each sub-model.

4.3.2.2. Calculate the weights and R. The weights of the parent nodes are

Table 6
The basic nodes keep the same state in 12 scenarios.

Factor category	Basic nodes	The state in 12 scenarios
Human and organizational factors	Fuel quality (ship)*	Qualified
	Fuel quality (icebreaker)*	Qualified
	Planned maintenance system (icebreaker)*	In position
	Planned maintenance system (ship)*	In position
	PMS training (icebreaker)*	Yes
	PMS training (ship)*	Yes
Technical factors related to ships and icebreaker	Maximum assisted ships' length	Medium
	Ship radar*	Failed: 1×10^{-3}
	Ship/icebreaker engine*	Failed: 1×10^{-3}
	Ship/icebreaker steering system*	Degraded: 1×10^{-3} Failed: 1×10^{-3}
	Draught	Full
	Icebreaker breadth	Large

(*Assumed information)

determined using the AHP approach based on expert input. Additional information on AHP can be found in [72]. Consider the 'look out (ship)' example, the specifics of the weights of parent nodes and the R computation are provided in Appendix E.

4.3.2.3. Determine the CPTs. Once the weights of parent nodes and the value of R index are established, the CPT for a single sub-model is determined using the three procedures in Section 3.2.3. Appendix E elaborates on the example of 'look out (ship)'.

4.3.3. The results

For each scenario, a comparison between the model output and the actual ship state is presented in Fig. 6.

The model output (i.e., the probability of ship besetting in ice calculated based on the input information, Tables 5-7 and CPT constructed by the method in Subsection 2.2.3) is represented by a black dot, with different colours and patterns demonstrating the real situation. Among the 12 scenarios, two scenarios (i.e., S8 and S11) are besetting in ice, one scenario (S5) is a difficult operation (based on the description in

Table 7
The input evidence of basic nodes for 12 scenarios (based on the information in the 'TIAN YOU' logbook, voyage summary report, AIS data).

Basic node	Scenario											
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Icebreaker speed	high	high	medium	high	low	high	medium	low	medium	high	low	medium
Ship speed	high	high	medium	high	low	high	medium	low	medium	high	low	medium
Distance between icebreaker and ship	long	long	moderate	long	short	moderate	moderate	short	short	moderate	moderate	long
Wind speed	slow	slow	slow	slow	slow	moderate	slow	moderate	slow	slow	moderate	slow
Wind direction	parallel	parallel	perpendicular	parallel	parallel	parallel	parallel	perpendicular	parallel	parallel	perpendicular	perpendicular
Current speed	slow	slow	slow	slow	slow	fast	fast	fast	slow	slow	fast	fast
Current direction	parallel	parallel	parallel	parallel	parallel	perpendicular	parallel	parallel	parallel	parallel	perpendicular	parallel
Ice concentration	low	medium	medium	low	high	medium	medium	high	medium	medium	high	medium
Ice type	light	thick	moderate	moderate	thick	light	moderate	thick	moderate	thick	thick	light
Visibility (ship)	good	good	low	good	good	good	good	low	low	low	good	good
Crew fatigue	moderate	light	light	moderate	severe	light	light	moderate	light	severe	moderate	severe
Navigation experience (ship)	medium	brief	medium	brief	medium	brief	medium	brief	medium	medium	brief	medium
Crew pressure	low	moderate	low	moderate	low	moderate	low	moderate	low	low	moderate	low
Level of training	extra	basic	extra	basic	extra	basic	extra	basic	extra	extra	basic	extra
Working years on this ship	low	low	low	low	low	low	low	low	low	low	low	low

the logbook), and the rest of the scenarios are not besetting in ice. Further, horizontal lines at 75.1% and 51.8 % correspond to the average probability levels for the two situations when besetting in ice occurred or did not, respectively.

5. Validation

5.1. Model validation

Owing to the development of BN using expert elicitation, validation is necessary. In this section, we focus on four types of validations and conduct a validity study by answering the questions in line with those recommended in [75].

5.1.1. Face validity

First, we discuss the face validity for the rationality and consistency of the BN with relevant studies and expert experience. Prior to developing the BN model, a relevant study on ship besetting in ice (Section 2) was conducted, which provides certain components of the developed models. Additional nodes were identified through an iterative discussion. Consequently, the developed BN was evaluated by a Captain (ref. Section 3.2, for details) who agreed on the structure of the model, emphasising that the four scenarios leading to the first assisted ship besetting in ice were plausible and that the relationships between variables were reasonable. Based on Captain's experience, risk factors such as wind and current, which have minimal effect on the ship manoeuvrability in the considered case, were eliminated, whereas the human and organizational factors, which affect the engine and steering system, were included. Thus, the resulting discretisation of the nodes is consistent with the literature and is in agreement with Captain's experience. Therefore, the face validity of the developed BN was considered to be high.

5.1.2. Content validity

To implement content validity, this section compares the factors considered in this model with those found in the literature.

5.1.2.1. The risk factors are not considered in this model. Most of the risk factors summarised in Table 1 were considered in the developed model. However, certain factors, which are not relevant to the output of the model, were excluded. The reasons for not considering these factors are discussed in the following paragraphs.

1) *Air and sea temperatures.* In [21], the air temperature affected the engine power, while sea temperature affected the ice concentration and thickness. Although the air temperature may affect the output of engine power, in the captain's experience, the human and organizational factors (including the PMS and fuel quality) take precedence over the air temperature factor. Further, the sea temperature depends on air temperature (and other factors); however, both the ice concentration and thickness (as observed by the onboard crew) were used as direct inputs in the proposed model.
2) *Wave height.* The wave height is considered to affect the engine power in [21], and ice concentration, and thickness in [22]. Based on similar reasons explained above, this study excluded the wave height.
3) *Distance from coastline.* Kubat [17] investigated 23 besetment events in the Gulf of St. Lawrence and the Strait of Belle Isle during the winters of 2013 and 2014, and analysed the relationship between ice pressure and distance from the coastline and between ridge thickness and distance from the coastline based on one besetment event information. Their results (Fig. 7) indicate that both the ice pressure and ridge thickness increase with proximity to the coastline. In contrast to the Canadian Arctic in winter, there was no landfast ice along the considered part of the NSR in August 2018 (Fig. 8), when

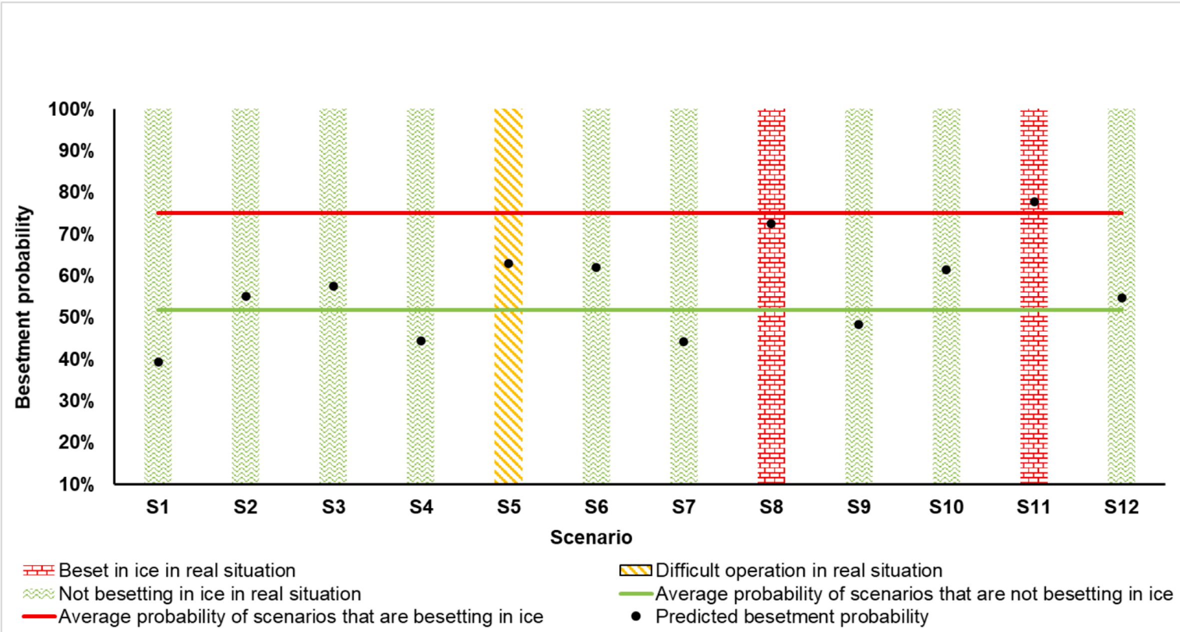

Fig. 6. The model's output and real situation for each scenario.

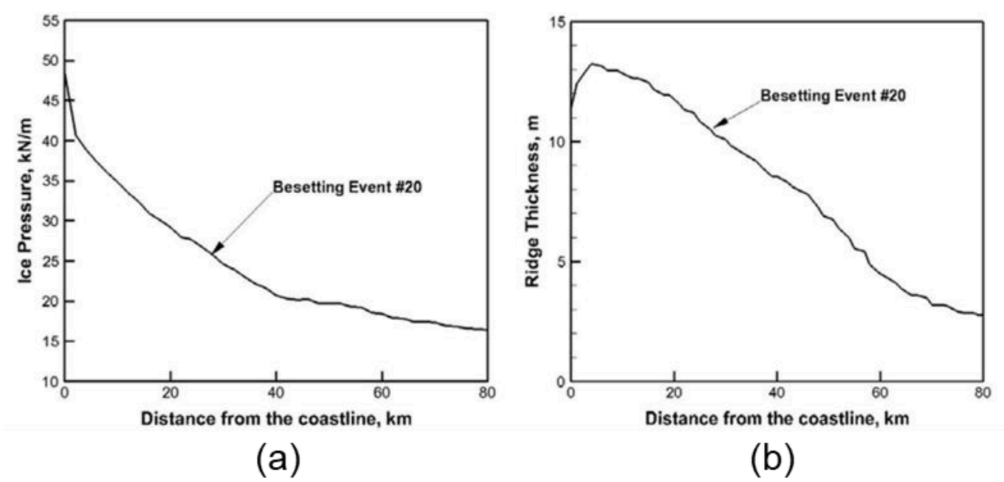

Fig. 7. (a) Ice pressure versus distance from the coastline, (b) Ridge thickness versus distance from the coastline [17].

commercial passages through the NSR were feasible. Therefore, the proximity-to-the-coastline factor was not considered. However, the distance from the coastline should also be considered during winter navigation along the NSR.

4) *Ice class and sea area*. Analysis of the besetment events [20] indicates that the ice class contributes considerably to ship besetment, where the geographical area (i.e., Barents Sea, Kara Sea, Laptev Sea, and East Siberian Sea) has minimal impact on the besetment frequency. Unfortunately, from the literature, it is not clear whether this observation is valid for both independently navigating vessels and vessels under icebreaker assistance. Undoubtedly, the ice class is a paramount factor for independent navigation, but under icebreaker assistance, in practice, the ship's speed would also be governed by the command from the icebreaker and not only by the vessel ice class and engine power.

5.1.2.2. The novel factors considered proposed model. In the developed model, we considered certain novel factors not considered in previous studies. In particular, these are the relative distance between the icebreaker and the ship, ice conditions in the ice channel, and human and organizational factors. Typically, the relative distance between ships, the state of the ice channel, and the fitness of the crew are essential in convoy operations. Further discussion on human and organizational factors is presented in Section 6.1.

5.1.3. Concurrent validity

It is impossible to conduct the concurrent validity of the current new model because of the lack of published models for estimating the ship besetment probability in a convoy operation.

5.1.4. Predictive validity

This section implements scenario and sensitivity analyses of the model to assess its predictive validity.

5.1.4.1. Model scenario analysis. We set the scenario nodes 'engine and steering system (ship)' and 'engine and steering system (icebreaker)' as failed. For both cases, the model predicted a 100 % probability of the ship besetting on ice. These two results are reasonable because in the

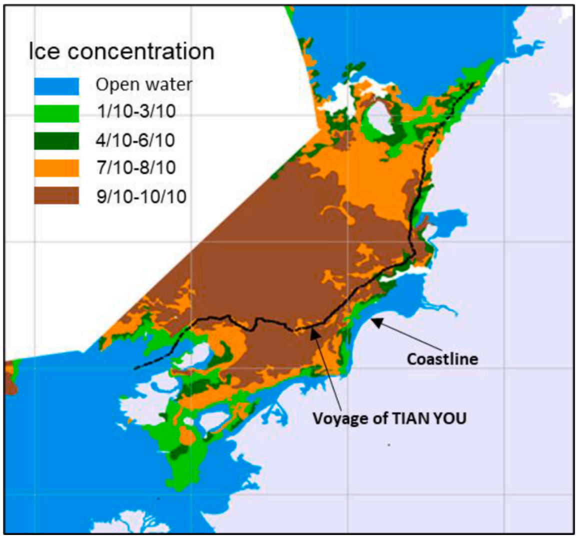

Fig. 8. Total ice concentration (3 August 2018) along the voyage of TIAN YOU (2 –7 August 2018). Ice concentration data (in SIGRID-3 format) are from the Arctic and Antarctic Research Institute.

real world, the ship will beset in ice once the ship or icebreaker loses its power.

Thereafter, we set the nodes 'engine and steering system (ship)' and 'engine and steering system (icebreaker)' as functioning and analysed the model output for the two following scenarios:

1) Set the node 'ship position with respect to the ice channel' as 'in the ice channel' and varied the state of 'conditions in the ice channel' as 'open', 'partially closed', and 'closed'. The corresponding model outputs were 1%, 46%, and 46 %, respectively, indicating that the ship has a significantly higher probability of besetting in ice when the ice channel is closed or partially closed compared to the situation when the ice channel is open.
2) Set the node 'ship position with respect to the ice channel' as 'deviation from the ice channel' and varied the state of 'conditions in the ice channel' as 'open', 'partially closed', and 'closed'. The model outputs were 16%, 93%, and 93 %, respectively, indicating that the ship has a higher probability of besetting in ice when it deviates from the ice channel compared with when it stays in the channel, and this is reasonable.

5.1.4.2. Sensitivity analysis. The purpose of a sensitivity analysis was to determine the changes in the target node when the basic node undergoes a small change [76]. If a small change in the basic node results in a substantial change in the target node, the latter is said to be sensitive to the basic node. Identification of sensitive nodes allows end-users of the BN to be aware of the effect of these nodes that can make the ship beset in ice. This study uses the Variation in the Probability of the Target Node (VPTN) to reflect the sensitivity degree of one basic node towards the target node. VPTN is the absolute difference of one state's probability of the target node caused by one basic node changing from one state to another.

The procedure for calculating the VPTN is as follows.

Step 1 Calculate the prior probability distribution of each basic node based on the input data for the 12 scenarios (Table 7). The resulting probability levels for each node state are listed in Table 8.
Step 2 Set the probability of State 1 (shown in Table 8) of one basic node to 100 %, and calculate the probability of one state of the target node.

Table 8
The prior probability of basic nodes.

Basic node	Prior probability distribution of states		
	State 1	State 2	State 3
Icebreaker speed	High 0.42	Medium 0.33	Low 0.25
Ship speed	High 0.42	Medium 0.33	Low 0.25
Distance between icebreaker and ship	Long 0.33	Medium 0.42	Short 0.25
Wind speed	Fast 0	Medium 0.25	Slow 0.75
Wind direction	Parallel 0.67		Perpendicular 0.33
Current speed	Fast 0.42		Slow 0.58
Current direction	Parallel 0.83		Perpendicular 0.17
Ice concentration	High 0.25	Medium 0.58	Low 0.17
Ice type	Thick 0.33	Medium 0.42	Light 0.25
Visibility (ship)	Good 0.75		Low 0.25
Crew fatigue	Severe 0.25	0.33	Light 0.42
Navigation experience (ship)	Rich 0	Medium 0.58	Brief 0.42
Crew pressure	High 0	Medium 0.42	Low 0.58
Level of training	Extra 0.58		Basic 0.42
Working years on this ship	High 0	Medium 0	Low 1

Step 3 Subsequently, set the probability of State 3 (shown in Table 8) of the basic node to 100 %, and calculate the probability of the state of the target node, similar to that in Step 2.
Step 4 Calculate the VPTN based on the two calculated probabilities of the state of the target node obtained from Steps 2 and 3.

As an example, consider the basic node 'ice concentration' and the target node 'ship besetting in ice'. When the ice concentration is in state 'high' (State 1) is 100 %, the probability of state 'yes' of the 'ship besetting in ice' is 63.8%. Thereafter, the state 'low' (State 3) is set to 100 %, and the probability of state 'yes' of the 'ship besetting in ice' is 41.8%. Therefore, the variation in the probability of 'ship besetting in ice' is 22% caused by 'ice concentration'.

Using this method (the above four steps), sensitivity analyses for three target nodes ('ship besetting in ice', 'ship position with respect to the ice channel', and 'conditions in the ice channel') were performed. The obtained results are summarised in Fig. 9, and the calculated VPTN values are listed in Table F1 in Appendix F for easy reference. According to Fig. 9, the main findings are as follows.

For the target node 'ship besetting in ice', ice concentration is the most important factor (21.9 %). The other two important factors are the distance between icebreaker and ship and the navigation experience (ship), both of which contribute more than 10 % to the variation in the probability of 'ship besetting in ice'.

The target node 'ship position with respect to the ice channel' is sensitive to most of the basic nodes. Moreover, among the basic nodes, navigation experience (ship) and icebreaker speed are the most two important factors that contribute more than 20% to the variation in the probability of 'ship position with respect to the ice channel'.

Regarding the target node 'conditions in the ice channel', ice concentration and distance between icebreaker and ship are the two most important factors, while the contribution of the remaining are much lesser.

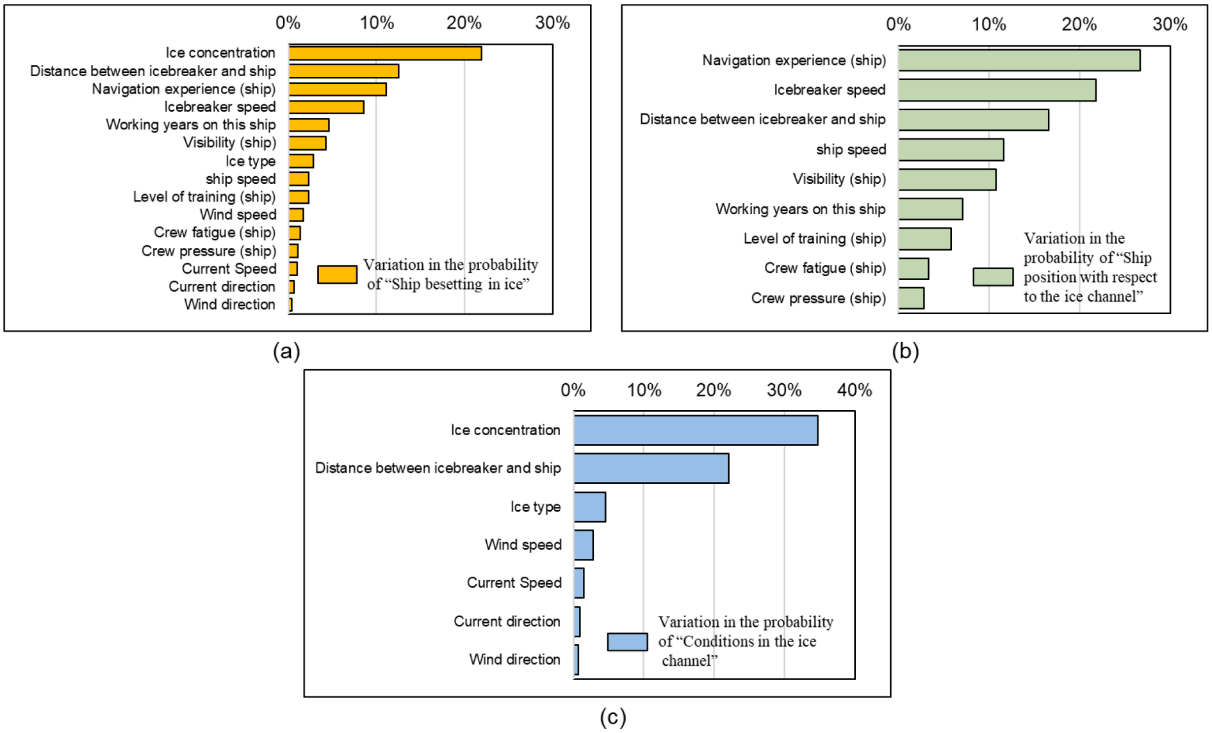

Fig. 9. Sensitivity of each basic node to the target node. (a) For the target node 'Ship besetting in ice'. (b) For the target node 'Ship position with respect to the ice channel'. (c) For the target node 'Conditions in the ice channel'.

6. Discussion

The discussion pertains to the following aspects from the development of the proposed BN model:

- Human and organizational factors in the convoy operation
- Challenges in calculation of CPTs
- Uncertainty analysis
- Model limitations
- Implications of the proposed model

6.1. *Human and organizational factors in convoy operations*

One innovation of the developed model is that it considers the human and organizational factors, thus enabling quantification of the effects of human factors on the probability of ship besetting in ice. The manner in which human and organizational factors can affect the operation during convoy operations based on the model results are as follows.

6.1.1. *Operating the ship within an insufficient radius of the ice channel*

Owing to the presence of multi-year ice flows and ice ridges, the ice channel created by the icebreaker is often curved. However, operating a ship in a curved ice channel is challenging, and any mistake may result in ship deviation from the ice channel, particularly when the radius of the ice channel is insufficient with respect to ship manoeuvrability characteristics but sufficient for the icebreaker. To investigate the contribution of human factors to operation in an insufficient radius of ice channel, we set the node 'radius of ice channel' as 100% insufficient in the developed model and employed the method discussed in Section 5.1.4.2. The variations in the probability of ship deviation from the ice channel caused by human factors are listed in Table F2 in Appendix F. The results show that the navigation experience contributes significantly to the scenario ship position with respect to the ice channel. In contrast, other human factors such as the level of training, working years on this ship, crew pressure, and fatigue, have much less impact on the scenario compared to the navigation experience.

6.1.2. *Impact on ship manoeuvrability*

In the proposed model, the working years of the ship and the level of training affect the ship manoeuvrability. Using the aforementioned method, the results show that a low number of working years on this ship can reduce the normal ship manoeuvrability by 42 % (Table F3 in Appendix F) compared to a larger number of working years on this ship. Whereas an extra level of training can increase the normal ship manoeuvrability by 18 % (Table F3 in Appendix F) compared to the basic level of training. This implies that familiarity with the characteristics of the equipment (ship response) is essential for operation in an ice channel.

6.1.3. *Look out (ship)*

In convoy operations, the assisted ship should pay attention to the icebreaker at all times. Therefore, it is essential to consider ship safety during convoy operations. In the proposed model, the inclusion of human factors such as level of training, crew pressure, navigation experience, and crew fatigue contribute to look out. The results show that the navigation experience can contribute to 44 % (Table F4 in Appendix F) variation in probability of 'look out' when its state changes from 'rich' to 'brief', while each of level of training, crew pressure, crew fatigue contributes to approximately 5 % (Table F4 in Appendix F) variation in probability of 'look out'.

6.2. *Challenges in calculation of CPTs*

The construction of CPT was based on the method outlined in Section 3.2.3 and was elaborate described in Appendix D and Appendix E, wherein the weights of parent nodes and R index were acquired using a questionnaire. However, decisions on the weights of each parent node to a child node vary from expert to expert. Consider the 'ship position with respect to the ice channel' as an example, the weights of four parent nodes were provided by the five experts, as shown in Table 9. The mean

Table 9
Weights of nodes assigned by experts (E1* has no ice navigation experience).

Parent nodes	The weights assigned by experts				
	E1*	E2	E3	E4	E5
Radius of ice channel	0.042	0.284	0.219	0.234	0.292
Look out (ship)	0.284	0.549	0.614	0.630	0.477
Collision risk	0.593	0.088	0.118	0.088	0.177
Ship manoeuvrability	0.081	0.079	0.049	0.048	0.054

values and standard deviations of the weights of each node are shown in Fig. 10. The values in Table 9 show that the weights of parent nodes can vary significantly among experts, particularly for the node 'collision risk', followed by 'look out (ship)' and 'radius of ice channel'. The most agreed upon weight is 'ship manoeuvrability'. A possible reason for this discrepancy may be the expert's background (e.g., it appears that the experts with ice navigation experience tend to place more importance on human factors (i.e., lookout) in contrast to the expert with no ice navigation experience (E1 scores in Table 9).

6.3. Uncertainty analysis

The case study of the proposed model is carried out based on the evidence recorded in the logbook of 'TIAN YOU'. The uncertainties of inaccuracies in expert judgment, data, modelling procedures that may influence the result are considered. The ratings for uncertainty estimation were proposed by [77] and applied in [78,79]. The brief interpretation of the rating is shown in Table 10, and the estimation for the uncertainty of the critical inputs of the model is shown in Table 11.

6.4. Limitations of the model

Because of the lack of risk models for convoy operations, certain risk factors were derived from the models applied for escort operations and independent navigation. However, this may result in certain relevant factors being ignored, although the nodes and states in the developed models have been discussed several times and verified by a captain. Consequently, input on the model structure and the influencing factors from several captains could be beneficial.

Further, the model was verified by cases in the summer season for a specific year and geographical location. Thus, certain disadvantages

Table 10
Interpretation of uncertainty ratings [77–79].

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 11
The uncertainty assessment for the case study.

Uncertainty element	Rating	Justification
Input data	Moderate	The data collected from the logbook, AIS, voyage summary report are recognized as trustworthy in Section 4.3.1. Because of the absence of knowledge about the icebreaker, the supposed statistics on the icebreaker may contain some inaccuracies.
Selected scenarios	Low	The selected 12 scenarios include all of the data required to calculate the result.
Correlation analysis	Low	The correlation between nodes in the model has been validated by one captain with substantial ice navigation experience. As a result, the uncertainty in variable correlation is low.
CPT	Moderate	Section 3.2.3 introduces the technique for calculating the CPT, and Appendix D and E detail the application in depth. Five experts were engaged in the estimate procedure. Among them, one expert has no expertise with ice navigation, while another is the chief officer with five years of experience, which may result in a tiny disparity between the provided and real weights of parent nodes. Two captains have extensive expertise with ice navigation but no academic background, which might result in some misunderstandings about the AHP approach. Additionally, the expert pool is limited to five persons, which may result in some score discrepancies (ref. Fig. 10). As a result, the CPT calculation might be considered as having moderate level of uncertainty.

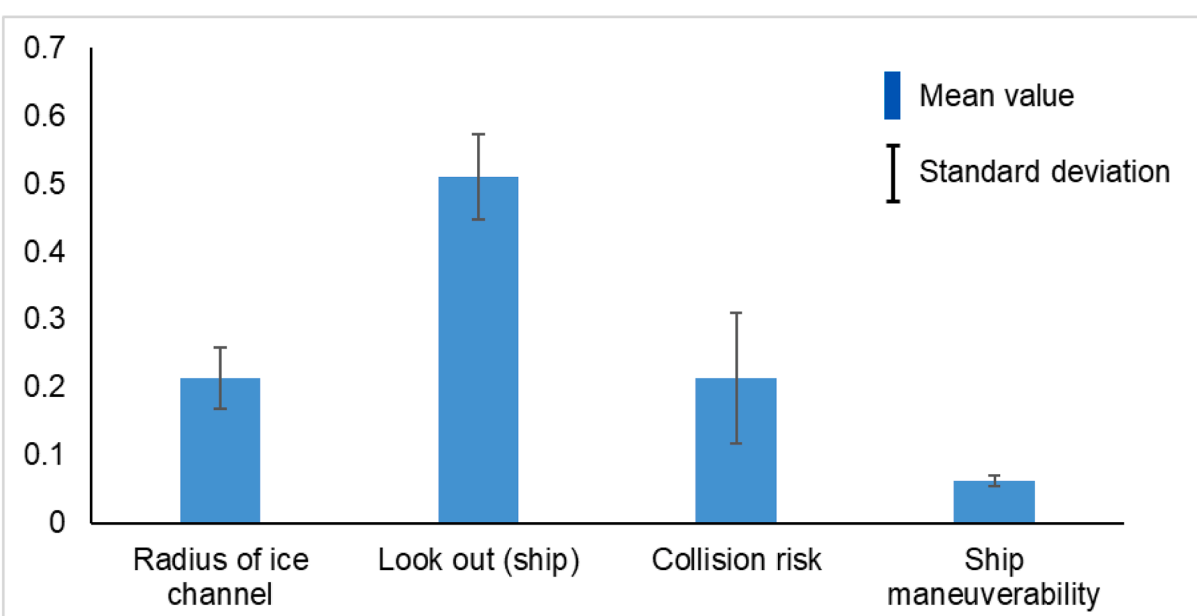

Fig. 10. The mean value and standard deviation of weights for each node.

may exist when using the model in the winter season because the model excludes the distance from the coastline factor. In addition, the engine power of the ship was not considered, and the model was limited to the first assisted ship in a convoy operation.

6.5. Implication of the proposed model

This study developed a BN model for estimating the probability of ship besetting in ice in a convoy operation. Earlier research on this topic did not focus on convoy operations and did not consider human and organizational factors. Therefore, to the best of our knowledge, the proposed model is the first to address this knowledge gap. This contributes to the body of knowledge regarding risks during Arctic convoy operations. The results of the case study indicate that this new model is feasible for estimating the probability of ship besetting in ice during a convoy operation along the NSR in summer. Moreover, the proposed model can potentially be used to support spatiotemporal risk assessments of ship besetting in ice events during convoy operations. For example, it can be used to estimate the dynamic probability of ship besetting in ice by a crew on board. In addition, it can also be applied for tactical route planning and supervisory risk control purposes. For tactical route planning applications, environmental factors can be obtained from forecast models, and the state of human factors can be estimated from the crew list and working schedules. The input data of dynamic ship factors (e.g., ship speed and relative distance between icebreaker and ship) can be populated based on the experts' judgment(s) and/or historical data (e.g., AIS data).

7. Summary and conclusive remarks

In this study, a new Bayesian Network model has been developed to predict the probability of the first assisted ship besetting in ice in a convoy operation along the Northern Sea Route, considering human and operational factors. The model considers a range of scenarios that can result in the besetment and several risk factors, including environmental factors, technical factors related to ship and icebreaker, and human and organizational factors. The model predictions have been validated using the actual data from the convoy transit along the Northern Sea Route in 2018, through scenario analysis and sensitivity studies. Further, different validity tests show that the model predictions are reasonable and consistent with the actual ship besetting in ice cases.

Key findings may be summarized as follows:

- The model indicates that the ice concentration factor contributes the most to the ship besetting in ice during a convoy operation, followed by the state of the ice channel and navigation experience.
- Among the considered human factors, the navigation experience contributes the most to look out and ship deviation from the ice channel. In addition, working years on this ship (or the familiarity of the crew with the characteristics of the equipment) is the most important factor affecting the ship's manoeuvrability.

The proposed model can be used in spatiotemporal risk assessment studies (e.g., for dynamic estimation of ship besetting in ice probabilities and route planning). However, applications of this model should be carefully handled because of the limitations in the validation datasets (NSR, summer season) and the disagreements among the expert scores in the calculations of CPTs.

CRediT authorship contribution statement

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

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the article entitled, *'A Bayesian Network Risk Model for Predicting Ship Besetting in Ice During Convoy Operations along the Northern Sea Route'*.

Acknowledgments

This work is a part of the NTNU Oceans Pilot Project—Risk, Reliability, and Ice Data in Arctic Marine Environment. The authors would like to thank Captain Alexandros Serpanos for his comments and discussion on the BN model and all experts participating in the estimation of the CPT, and COSCO SHIPPING Specialized Carriers Co., Ltd. for providing the voyage data of TIAN YOU for this study. The first author thanks Nabil Panchi for help with processing and visualizing ice concertation data in Fig. 8.

Supplementary materials

Supplementary material (including references [80–91]) associated with this article can be found, in the online version, at doi:10.1016/j.ress.2022.108475.

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