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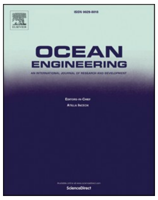

Hybrid causal logic model for estimating the probability of an icebreaker–ship collision in an ice channel during an escort operation along the Northeast Passage

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ABSTRACT

Under severe Arctic ice conditions, escort operations are the most efficient methods for facilitating shipping. Nevertheless, escort operations are among the most dangerous operations, as they may result in icebreaker–ship collisions and/or ship besetting in ice. To mitigate the risk of collisions, it is essential to understand the event sequences of collisions and the risk control options that can be implemented to reduce the occurrence of undesired events. This paper proposes a hybrid causal logic model to estimate the likelihood of an icebreaker–ship collision while considering human factors during an escort operation along the Northeast Passage. The model relies on inputs from four icebreaker captains. Its applicability is demonstrated for a 2018 summer voyage of a cargo ship assisted by an icebreaker. Risk control options are then proposed based on qualitative and sensitivity analyses of the model. The results of this study can assist shipping companies to better understand the sequence of events prior to icebreaker–ship collisions during escort operations in ice-covered waters. This paper provides information on risk reduction measures. In addition, the proposed model can assist in route planning.

1. Introduction

Under the influence of climate change, the Arctic ice reached its annual minimum extent on September 18, 2022, which was the tenth lowest in the nearly 44-year satellite observation record (Gautier, 2022). Between 1980 and 2008, ice thickness in the Arctic Ocean decreased by an average of 1.3–2.3 m according to the records of the Norwegian Polar Institute (Norwegian Polar Institute, 2013). These changes enable more Arctic shipping to be conducted in ice-prone regions (Fu et al., 2021; Pizzolato et al., 2016). According to data from the Protection of the Arctic Marine Environment (PAME), the number of unique ships in the Arctic area increased by over 25% between 2013 and 2019 (PAME, 2020), as defined by the Polar Code (IMO, 2014). However, the ice conditions in the winter season and in some areas (e.g. the East Siberian Sea) in the summer season remain a challenge for ships to navigate (Marchenko, 2012). In addition, harsh environments (e.g. darkness, low temperatures, rapid changes in ice conditions due to ice drift), a lack of infrastructure, inexperience in Arctic navigation, etc., make shipping operations difficult (Kujala et al., 2019; Shu et al., 2023).

Assistance from icebreakers can facilitate Arctic shipping. Generally, the operation modes under icebreaker assistance can be divided into the following four categories: (1) escort operations, (2) convoy operations, (3) breaking ship loose operations, and (4) towing operations (Goerlandt et al., 2017; Kujala et al., 2007; Xu et al., 2021). Although icebreaker assistance reduces the likelihood of accidents, such as ship–ice collisions and rudder and propeller damage (in comparison with independent navigation), a collision between the icebreaker and assisted ship is more likely because of their close proximity (Franck and Holm Roos, 2013; Zhang et al., 2020a,b,c,d). Accident statistics for the Russian sea area (Zhang et al., 2019) and Finnish sea areas (Valdez Banda, 2017) are depicted in Fig. 1. Collisions between icebreakers and ships account for 95% and 55% of all accidents in the Finnish and Russian sea areas, respectively. A collision between an icebreaker and a ship can inflict severe structural damage to both vessels, even rendering the icebreaker inoperable for an extended period as it undergoes repairs (SENDA, 2019). Such accidents may result in oil spills, causing environmental damage and ecosystem destruction (Helle et al., 2020; Afenyo et al., 2016, 2019; Bambulyak and Ehlers, 2020; Goerlandt and Montewka, 2015). Therefore, all parties involved in the use and development of the Northeast Passage, including authorities, search-and-rescue organisations, shipping companies, engineers, insurers, lawyers, and local communities, should appreciate the potential hazards of icebreaker–ship

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collisions and take proactive measures to mitigate the associated risks. Thus, they can safeguard those operating in the region, protect the environment, and ensure the smooth functioning of shipping activities (Chen et al., 2019, 2018; Li et al., 2023; M. Li et al., 2021a; Montewka et al., 2014, 2012; Xie et al., 2023).

To better understand and mitigate the risks associated with icebreaker–ship collisions, researchers have focused on collecting and analysing collision cases and identifying the most common causes and contributing factors, as highlighted in several studies. Franck and Holm Roos (2013) compiled ten collision cases involving escort/convoy operations in the Baltic Sea from 1985 to 2012 and identified the causes of each collision. Zhang et al. (2019) collected 17 collision cases in the Baltic Sea (16 cases) and the Arctic (1 case) between 1989 and 2017 and classified the causative factors using the human factors analysis and classification system. Subsequently, a fault tree (FT) model was developed to qualitatively analyse the collision between an icebreaker and assisted ship. Valdez Banda et al. (2015) analysed accident data extracted from four winter periods in the Baltic Sea and discovered that collision was the most common accident type and that ice thickness between 0.15 and 0.4 m contributed the most to collisions. Kum and Sahin (2015) used a root cause analysis to study data from the Marine Accident Investigation Branch. Based on the results of the investigation, an FT of the collision was developed that focused on independent navigation and navigation with icebreaker assistance.

Efforts have been made to determine the distance required to prevent collisions during escort/convoy operations. Zhang et al. (2017) calculated the safe distance between an icebreaker and escorted ship based on ship-following theory. The calculation considered the acceptable ship collision frequency, ice conditions, and ship characteristics (ship length, ice class, and ship speed). Zhang et al. (2018)a,b created a model to simulate ship-following behaviour under ice conditions. The model was developed by considering the safe distance, safe speed, ice conditions, and the ship's ability to transit icy regions. Additionally, the model was enhanced by incorporating the influence of communication between ships (Zhang et al., 2020a,b,c,d). Khan et al. (2019) developed a Bayesian Network (BN) integrated with the Nagel–Schrekenberg model to analyse the probability of collisions during convoy operations. The Nagel–Schrekenberg model was adopted to estimate the ship density in convoy operations, which affects the following two factors: maintaining a safe distance between ships and maintaining a safe speed. Liu et al. (2022) identified 239 icebreaker assistance operations (159 escort operations and 80 convoy operations) in the Baltic Sea based on a proposed automatic identification system, and the relative distance was statistically examined.

Additionally, the recommended distance between ships has been emphasised in several guidelines (books) and considers the following two aspects: (1) the minimum distance necessary to prevent a collision between the ship and icebreaker and (2) the maximum distance necessary to prevent the ice channel from closing and trapping the ship in ice (Canadian Coast Guard, 2012; Sinder, 2018). The recommended distance under different ice conditions in the Baltic Sea (Buysse, 2007) is as follows: 1) in light ice conditions, the distance should be kept between 3 and 5 cables (555–926 m); 2) in moderate ice conditions, the distance should be kept between 2.5 and 3 cables (463–555 m); 3) in severe ice conditions, the distance is reduced to 1–1.5 cables (185–278 m), or even 5–10 m.

The existing literature on collisions in escort/convoy operations in icy waters focuses on cause analysis and safe distance, with a particular emphasis on the Baltic Sea region. However, an important knowledge gap is the lack of investigation into the event sequence leading to icebreaker–ship collisions in ice channels, which is a crucial aspect from a risk assessment perspective during escort operations. This study aimed to address this gap. The main contributions of this study are as follows:

- A new hybrid causal logic (HCL) model is proposed for estimating the probability of an icebreaker–ship collision in an ice channel while considering human factors.
- Data collected from a voyage of the vessel TIAN HUI escorted by the icebreaker VAYGACH in August 2018 were analysed in view of the probability of icebreaker–ship collision.
- A proposal for risk control options (RCO) from multiple perspectives, including icebreaker and shipping companies and onboard crews of both icebreakers and ships.

The remaining sections are organised as follows: Sections 2 and 3 introduce the methodology and collision model construction, respectively. Section 4 presents a case study demonstrating the applicability of the model based on a real journey. Section 5 discusses the findings and presents measures to reduce collision risk. Finally, concluding remarks are presented in Section 6.

2. Methodology

HCL is a modelling and quantification framework for accident scenarios (An accident scenario is defined as a sequence of events from an initiating event to an end event with undesired consequences). HCL has

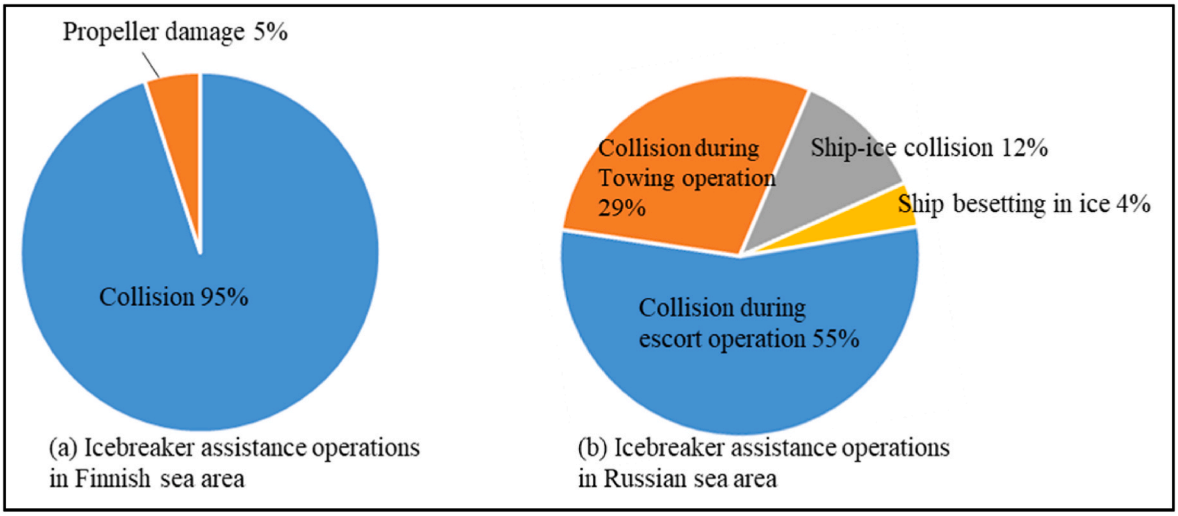


Fig. 1. Types of accidents occurring during winter navigation under icebreaker assistance. (a) Winter seasons in 2002–2003, 2009–2012 (Valdez Banda, 2017). (b) Data replotted from Zhang et al. (2019).

successfully been applied to ship collision (Pedersen, 2021; Wang et al., 2020), ship foundering (Zhang et al., 2018a,b), autonomous vehicle (Thomas and Groth, 2021), offshore platform (Røed et al., 2009; Wang et al., 2011), and nuclear power plant (Diaconeasa, 2017) risks. It includes an event sequence diagram (ESD), FT, and BN (Fig. 2). The FT approach is commonly considered a superior option for technical considerations, whereas the BN approach excels in addressing human and organizational factors (Zhang et al., 2020a,b,c,d; Fan et al., 2020a, 2020b) and an uncertainty perspective (Goerlandt and Reniers, 2017). The result of combining FTs and BNs is typically a risk model with greater details and resolution compared with conventional FT tools (Røed et al., 2009; Wang et al., 2020). The ESD approach clearly demonstrates the sequence of events from the initiating event (IE) to the end state (ES). The quantification of events in an ESD can provide insights into the causes of icebreaker–ship collisions. Correspondingly, risk-mitigation measures have been implemented to reduce the occurrence of collisions. Details of the ESD, FT, and BN modelling approaches are available in Rausand and Haugen (2020). The following paragraphs present summaries of the approaches necessary to understand the HCL model.

2.1. Event sequence diagram

The ESD captures all the possible ESs and related sequences of intermediate events caused by the IE, resembling an event tree (Fu et al., 2018; Stanton et al., 2022). Identifying the IE is the initial step in the development of ESD. The responses of the system (i.e. icebreaker and assisted ship) following the identified IE are called pivotal events (PEs) in the ESD. Pivotal events may be functions or failures of barriers and may also be events or states. The final event in the ESD is called the ES, as shown in the ESD section of Fig. 2. The ESD begins with the IE and splits at certain stages in the structure. Splitting occurs during pivotal events. The ESD can identify accident scenarios that follow the IE and determine and evaluate the spectrum of consequences. The events in an ESD can be further analysed using FT and/or BN sequences for each accident scenario.

2.2. Fault tree

FT analysis is the most commonly used method for the causal analysis of hazardous events in risk analyses (Ugurlu and Cicek, 2022; Zhao et al., 2022). It is a deductive method in which backward reasoning is used to determine the causal sequence of a specific event. A specific event at the top of the FT in the diagram is referred to as the top event. The immediate causal events E_1, E_2, …, E_n that, individually or in combination, lead to the top event are identified and linked to the top event via a logic gate (see Table 1). Subsequently, all potential causal events $E_{i,1}$, $E_{i,2}$, …, $E_{i,n}$ that may lead to event E_i for $i = 1, 2, \ldots$ are identified and linked to event E_i through a logic gate. This procedure is repeated until a suitable level of specificity is achieved. These events constitute the basic events (BEs) of the FT. Binary analysis is used in the FT analysis. All events from the top event to the basic events were assumed to be binary events that either or do not occur. BEs, such as human and organizational factors, can be further analysed using a BN.

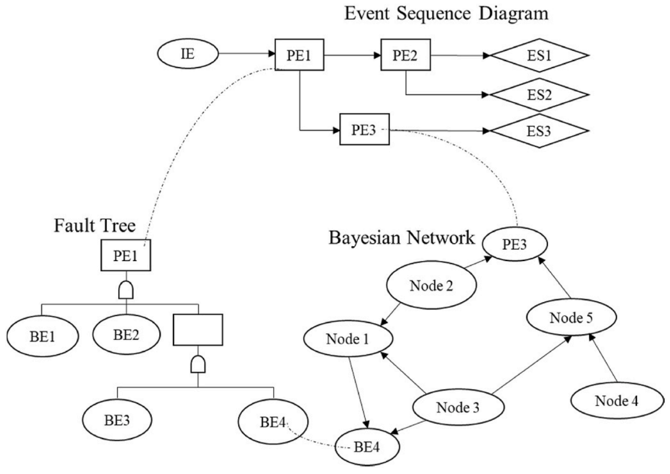


Fig. 2. HCL framework (Røed et al., 2009; Yang et al., 2017).

2.3. Bayesian network

BNs are directed acyclic graphs belonging to a family of graphical models. The causal relationship between the variables is depicted using arcs/lines. It comprises the following three parts (Xu et al., 2022b):

Element 1 node, which indicates the variables;
Element 2 node-directed arcs/lines with arrows, which indicate the causation relationships between nodes;
Element 3 conditional probability table (CPT), which contains the conditional probability of each node state to quantify the causation relationship.

A BN can express the combinations of complex system variables, incorporate new observations, and interpret inherent causal factors and their associated probabilities of occurrence (Afenyo et al., 2017; Baksh et al., 2018; Fu et al., 2016; Goerlandt and Montewka, 2014; Mazaheri et al., 2016; Montewka et al., 2015; Valdez Banda et al., 2016; Zhang et al., 2013). Jensen and Nielsen (2007) and Langseth and Portinale (2007) provided additional information regarding BNs.

2.4. Hybrid causal logic

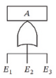
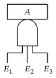
In this study, the HCL modelling approach was adapted to analyse icebreaker and ship collisions through the following steps:

(1) Identifying IEs and developing the ESD;
(2) Constructing the FT or BN to analyse the causes of events in the ESD;
(3) Constructing the BN for BEs in the FT
(4) Identifying the CPT of the BN;
(5) Assigning the probability of BEs/nodes;
(6) Calculating the probability of collision.

3. Model construction

The literature review shows that, in contrast to the Baltic Sea, the Arctic areas along the Northeast Passage lack accident reports that can be used to reconstruct collision models. Thus, the construction of the model in this study (including the identification of events, underlying risk factors, and their relationships) primarily relied on the elicitation of icebreaker captains (from a total of four captains). The modelling process consisted of the following three steps:

Table 1
Logic gates of a fault tree (Rausand and Haugen, 2020).

Logic gates	Symbol	Description
OR		Event A occurs if at least one of the causal events E_i occurs
AND		Event A occurs only when all the causal events of the causal event E_i occur at the same time

1) Preliminary model. The preliminary model was developed based on the literature, the navigation experience of the first author, and author discussion.
2) Captain elicitation. To revise the preliminary model, two meetings with two icebreaker captains for each (four captains in total) were conducted.
3) Final model. The refined model based on captains' feedback was presented to the captains, who agreed with the model's structure.

The following sections describe the structure of the proposed model.

3.1. Modelling the ESD

In escort operations, the events that initiate a collision are defined as follows: 1) the icebreaker substantially reduces its speed or stops, and 2) the speed of the ship increases. The ESDs are illustrated in Fig. 3.

3.1.1. ESD1 initiated by event 'icebreaker reduces its speed substantially or stops'

The four scenarios caused by IE1 are shown in Fig. 3. Normal operating conditions, i.e. a safe distance between the icebreaker and escorted ship is assumed before IE1 and IE2. The event sequences presented below were verified by the four captains.

Regarding the sequence {IE1→PE1→PE2→Collision/No collision} in Fig. 3, when the icebreaker reduces its speed substantially or stops, the event in which the 'ship identifies the situation in a timely manner' plays a barrier role in avoiding the collision. If the ship's crew fails to recognise this situation in a timely manner, the relative distance between the ship and icebreaker may be insufficient for the ship to stop. Subsequently, the ship makes every effort to leave the ice channel. If this operation fails, it is impossible to avoid a collision (Scenario 1). No collision (Scenario 2) is assumed if the ship leaves the ice channel.

For the sequence {IE1→PE1→PE3→Collision/No collision} in Fig. 3, when the event of 'ship identifies the scenario in a timely manner' occurs (i.e. PE1 is 'No'), the assisted ship will immediately decrease its speed and will attempt to stop to avoid collision. 'Leaving the ice channel' is not considered in this event sequence because the reduced ship's speed diminishes the ship's manoeuvrability and capacity to leave the ice channel after PE3. However, note that if the distance between the icebreaker and the ship is not initially safe, after 'ship identifies the scenario in a timely manner', the assisted ship will select to leave the channel to avoid collision.

3.1.2. ESD 2 initiated by event 'ship increases its speed in the ice channel'

In an escort operation, the escorted ship may increase its speed for greater manoeuvrability or under low-visibility conditions, resulting in an insufficient distance between the icebreaker and ship. Subsequently, the ship reducing its speed in a timely manner determines whether a collision occurs between the icebreaker and the ship (see Fig. 3). 'Leaving the ice channel' is not considered in this event sequence for similar reasons stated in Section 3.1.1.

3.2. Modelling the events in ESD1

3.2.1. Modelling of IE1

In the Arctic, icebreakers and ships frequently encounter thick first-year and/or multiyear ice and ice ridges (Montewka et al., 2018). A harsh ice environment results in the icebreaker decreasing its speed substantially or stopping. This event can be caused by 'icebreaker technical failure' or 'the icebreaker fails to proceed in ice' event. 'Icebreaker steering system failure' and 'icebreaker engine failure' are the causes of 'icebreaker technical failure' (Kum and Sahin, 2015; Xu et al., 2022b; Zhang et al., 2019). The reasons for 'the icebreaker fails to proceed in ice' are the 'icebreaker crew fails to find an easy way' and 'icebreaker fails to break ice' (Kum and Sahin, 2015). 'Low technical icebreaking capacity' and 'severe ice environment' are the causes of the 'icebreaker fails to break ice'. The event in which the 'icebreaker crew fails to find an easy way' may be caused by the following six events: 'darkness', 'low visibility', 'thick snow covers ice', 'high ice compression', 'lack of updated information', and 'insufficient crew fitness' (Afenyo et al., 2017; Baksh et al., 2018; Khan, 2020; Montewka et al., 2015; Zhang et al., 2020a,b,c,d, 2022a,b; Zhang et al., 2022a,b; Zhang et al., 2020a,b,c,d). The FT model is shown in Fig. 4. The events 'insufficient crew fitness' and 'severe ice environment' are further modelled using BN1 and BN2, respectively (Fig. 4). The 'crew fitness' is affected by 'navigation experience', 'fatigue', 'crew pressure', and 'level of training' (Xu et al., 2022b). According to the recommendations of four experienced captains, the 'ice environment' can be described by 'ice type', 'ice concentration', 'ice ridge', and 'ice compression'.

3.2.2. Modelling of PE1

PE1 is modelled using FT2 (Fig. 4). The events 'insufficient lookout (ship)' and 'failure to get the alert from the icebreaker' are identified as the two main causes for PE1. The event 'insufficient lookout' is further analysed using BN3 in Fig. 4, which contains the following four factors: 'number of officers on watch', 'visibility', 'ship radar', and 'crew fitness'. The 'failure to get the alert from the icebreaker' is caused by 'language

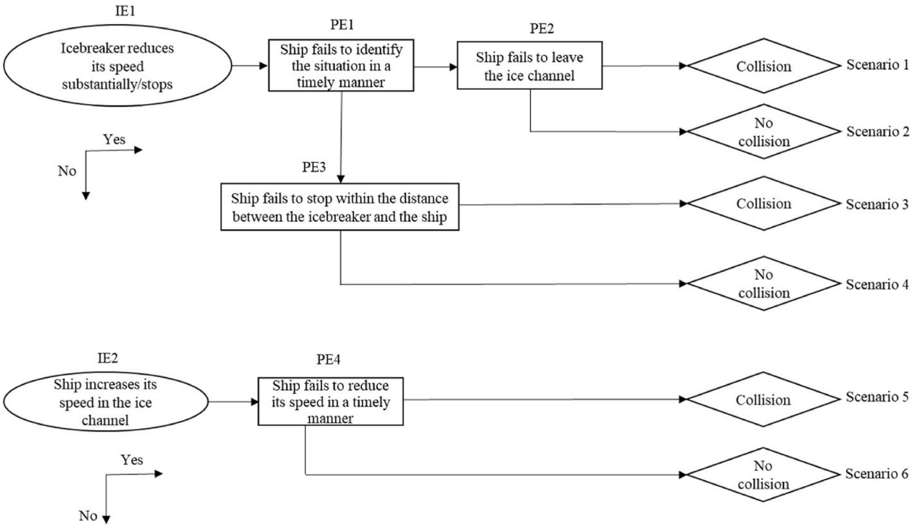


Fig. 3. ESD of 'icebreaker reduces its speed substantially or stops' and of 'ship increases its speed in the ice channel' (IE: initiating event, PE: pivotal Event).

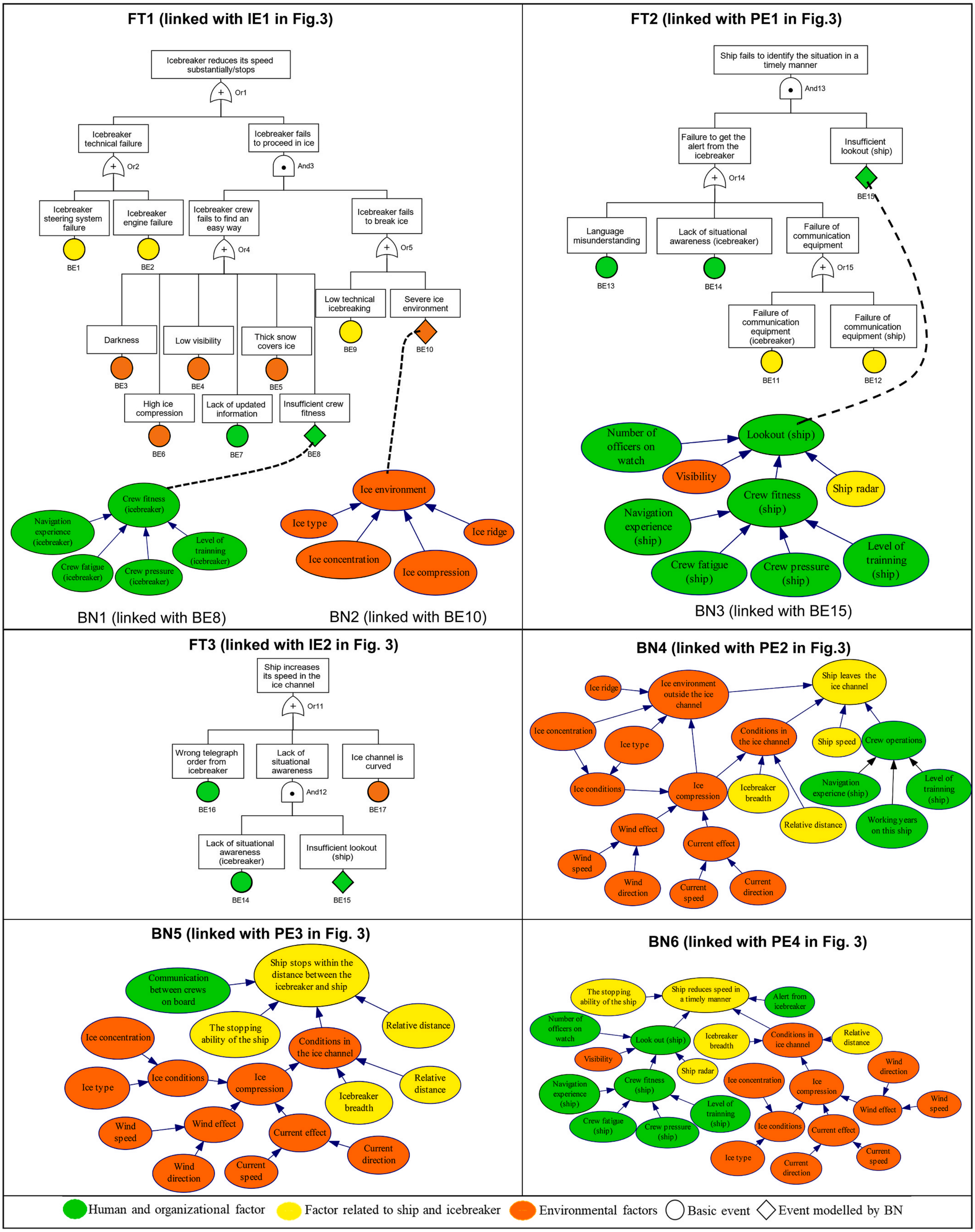


Fig. 4. FTs and BNs developed for events in the event sequence diagram. FT: fault tree, BN: Bayesian network, BE: basic event, IE: initiating event, PE: pivotal event.

misunderstanding', 'failure of communication equipment', and 'lack of situational awareness (icebreaker)' (Boström, 2020). The 'failure of communication equipment' refers to the failure of the icebreaker and/or the ship's communication equipment.

3.2.3. Modelling of PE2

PE2 is analysed in BN4 (Fig. 4). The 'ship leaves the ice channel' is influenced by the following four factors: 'ice environment outside the ice channel', 'conditions in the ice channel', 'ship speed', and 'crew operations'. The severe 'ice environment outside the ice channel' acts as a fender to prevent ships from leaving the ice channel, and is described by the 'ice concentration', 'ice type', 'ice compression', and 'ice ridge' (ref. Appendix Table A for a detailed description of the nodes and their discretisation). Sufficient ship speed is critical for the ship to leave the ice channel; however, conditions in the ice channel (e.g. ice channel closure) will reduce the ship's speed. The 'conditions in the ice channel' are affected by 'ice compression', 'icebreaker breadth', and 'the relative distance between the icebreaker and ship' (Xu et al., 2022b). The 'ship leaves the ice channel' is also influenced by the ship 'crew operations'. 'Crew operations' are affected by 'navigation experience', 'level of training', and 'working years on the ship'.

3.2.4. Modelling of PE3

PE3, which is influenced by the 'communication between the crew on board', 'stopping ability of the ship', 'conditions in the ice channel', and 'relative distance', is modelled using BN5 in Fig. 4. Clear and timely communication on board is essential to ensure the prompt stopping of the ship. The ship's stopping ability is related to its speed, loaded conditions, etc. The resistance caused by the ice in the ice channel makes it easier to stop the ship. The initial relative distance between the icebreaker and the ship critically affects whether the ship can stop within the relative distance.

3.3. Modelling the events in ESD2

3.3.1. Modelling of IE2

There are three possible reasons for the ship increasing its speed in the ice channel. An incorrect telegraph order from the icebreaker, particularly when the icebreaker sends an engine order instead of a speed order, can result in an increase in ship speed. When a crew member is fatigued, the lack of awareness increases the speed of the ship. This includes both icebreakers and ships. A curved ice channel is one of the factors that encourages a ship to increase its speed to improve its manoeuvrability and avoid becoming ice-bound. This model is displayed in FT3 in Fig. 4.

3.3.2. Modelling of PE4

After the ship increases its speed, it must be immediately reduced to avoid a collision. Speed reduction depends on the stopping ability of the ship. The ice in the ice channel slows the ship because of its resistance and friction. Alerts from icebreakers and lookouts from ships are human and organizational factors that affect ship speed reduction.

4. Case study

To demonstrate the applicability of the proposed HCL model, we studied an actual escort operation, which is described below.

In 2018, the cargo ship TIAN HUI was escorted eastbound by the icebreaker VAYGACH along the Northeast Passage (Fig. 5). This escort operation began at 75°08′N/154°58′E, 1200 UTC on 29th July 2018 and ended at 68°26′N/176°43′E, 1830 UTC on 2nd August 2018. During this escort operation, eight pieces of waypoint information (heading course, speed, wind force, wind direction, visibility, and ice conditions) were recorded by the crew on board. The data in this section were derived from the automatic identification system (AIS) data (including time, vessel position, speed, and heading course), a copy of the ship's logbook, and some captain-written voyage reports. The AIS data were obtained from Shipfinder (2022), and other sources were supplied by COSCO SHIPPING Specialized Carriers Co., Ltd. Ice conditions along the voyage are presented in Table 2 and details of the ship information are presented in Table 3.

Table 2
Ice concentration and ice thickness along the voyage.

Waypoint No.	Reported total ice concentration (from ship's logbook)	Estimated ice thickness (m) (from the sea ice dataset ARCTIC_MULTIYEAR_PHY_002_003)
WP1	10/10	2.22
WP2	7/10	1.95
WP3	10/10	1.88
WP4	9/10	1.5
WP5	3/10	0.6
WP6	1/10	0.47
WP7	7/10	1.3
WP8	5/10	0.31

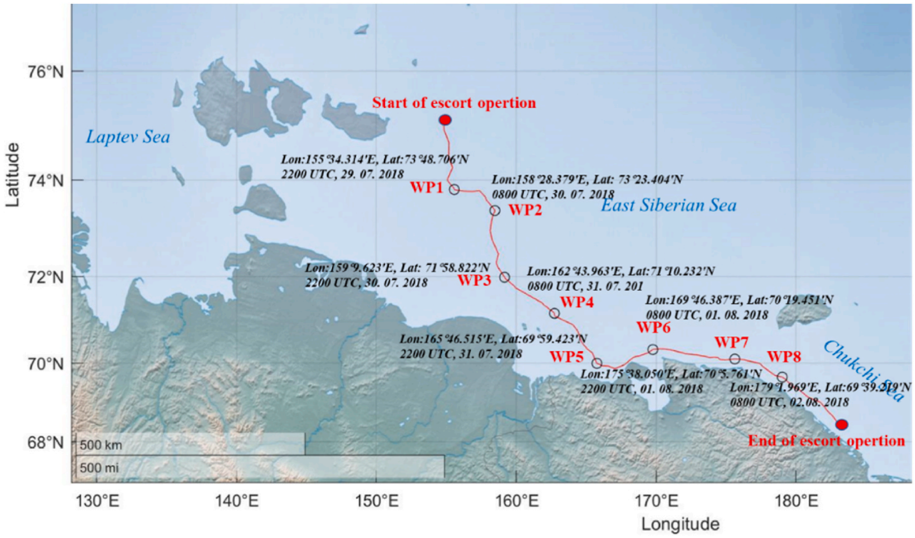


Fig. 5. Trajectory of the escort operation on the Northeast Passage (WP: waypoint).

Table 3
Ship information details for the escort operation.

	Icebreaker	Assisted ship
Ship name	VAYGACH	TIAN HUI
Ice class	RMRS LL2	FS Ice Class 1A
Length	149.7 m	186.4 m
Ship's width	28 m	28.50 m
Depth	15.68 m	15.80 m
Draught	9 m	11.00 m
Maximum speed	18.5 kn	14.80 kn
Construction year	1990	2017

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

4.1. Calculation process

To quantify the collision risk of this voyage, we assigned probabilities to the basic events in the FTs and basic nodes in the BNs. The following section explains the assignment of probabilities to basic events/nodes and the determination of CPT for BN.

4.1.1. Probability of basic events/nodes

To assess the probability of collision during this voyage, the first step was to assign the probabilities of basic events in the FTs and basic nodes in the BNs. In FT1, the failure of the engine (BE1) and failure of the steering system (BE2) during the escort operation were considered to be 1×10^{-3} owing to the low temperature and frequently changing speed and course (Xu et al., 2022b). The probabilities of darkness (BE3) and snow cover (BE5) were zero during summer. The low visibility (BE4) probability was calculated based on the voyage logbook records and was equal to 0.25. Because the voyage occurred during the summer, the ice along the coastline had melted. Therefore, high ice compression (BE6) was considered to not exist. The lack of updated information (BE7) may lead the ship operator to travel the wrong route, but the probability of this was assumed to be as low as 5.3×10^{-4} (Baksh et al., 2018). Crew fitness (icebreaker) (BE8) was affected by navigation experience, crew fatigue, crew pressure, and training level. It was further modelled by BN1 (Fig. 4), and the probabilities are listed in Table 4. The descriptions of the nodes in the BNs are presented in Table A of the Appendix. VAYGACH can break ice (BE9) up to 2.2 m at a speed of 3 knots. Ice is the spatial average of ice along the voyage, which was derived from the Arctic Ocean Physics Reanalysis data (Copernicus Marine Service, 2022). The probability of ice thickness greater than 2.2 m was calculated, which was the input probability of BE9. The ice environment is reflected by the ice type, ice concentration, ice ridge, and ice compression, which were further modelled by BN2 (see Fig. 4). The ice concentration and type were derived from the records of the voyage logbook and Arctic Ocean Physics Reanalysis data (Copernicus Marine Service, 2022), respectively. Ice ridging is dominated by the ice concentration. The frequently quoted ice concentration threshold for ridging was 0.8 (Løset et al., 2006). These probabilities are listed in Table 4.

In FT2, the failure of the communication equipment can be caused by the failure of the icebreaker's communication equipment (BE11) and the failure of the ship's communication equipment (BE12), and the failure probability was considered to be 5.6×10^{-2} (Baksh et al., 2018). The working language on board is English (IMO, 2001), and crew members from different countries may have different accents and cultures, which can further lead to communication misunderstanding (BE13). This probability can be as low as 7×10^{-4} (TÖZ et al., 2021). The lack of situational awareness (icebreaker) (BE14) refers to the statistical

Table 4
Input data for BNs.

NO.	Target variable	Parent variables	State1	State2	State3
BN1	Crew fitness (icebreaker)	[a]Navigation experience (icebreaker)	Rich: 100%	Medium: 0	Brief: 0
		[a]Crew fatigue (icebreaker)	Severe: 0	Moderate: 0	Light: 100%
		[a]Crew pressure (icebreaker)	High: 0	Moderate: 0	Low: 100%
		[a]Level of training (icebreaker)	Extra: 100%	–	Basic: 0
BN2	Ice environment	Ice type	Thick: 50%	Moderate: 12.5%	Light: 37.5%
		Ice ridge	Yes: 37.5%	–	No: 62.5%
		Ice compression	High: 0	Medium: 0	Low: 100%
		Ice concentration	High: 37.5%	Medium: 37.5%	Low: 25%
BN3	Lookout (ship)	Number of officers on watch	Sufficient: 100%	–	Insufficient: 0
		Visibility	Good: 62.5%	Moderate: 12.5%	Low: 25%
		[a]Ship radar	Functioning: 0.999	–	Failed: 1×10^{-3}
		Navigation experience (ship)	Rich: 0	Medium: 33.3%	Low: 66.7%
		[a]Crew fatigue (ship)	Severe: 33.3%	Moderate: 33.3%	Light: 33.4%
		[a]Crew pressure (ship)	High: 33.3%	Moderate: 33.3%	Low: 33.3%
		Level of training (ship)	Extra: 100%	–	Basic: 0
BN4	Ship leaves the ice channel	[#BN2]Ice environment outside the ice channel	Severe: 19.7%	Medium: 49.5%	Light: 30.8%
		Conditions in the ice channel	Open: 74%	Partially closed: 22%	Closed: 4%
		Ship speed	High: 71.5%	Medium: 27.1%	Low: 1.4%
		Navigation experience (ship)	Rich: 0	Medium: 33.3%	Brief: 66.7%
		Working years on this ship	High: 0	Medium: 0	Low: 100%
		Level of training (ship)	Extra: 100%	–	Basic: 0
BN5	Ship stops within the distance between the icebreaker and ship	[a]Communication between crews onboard	Sufficient: 100%	–	Insufficient: 0
		The stopping ability of the ship	Strong: 1.3%	Medium: 27.2%	Low: 71.5%
		Conditions in the ice channel	Open: 74%	Partially closed: 22%	Closed: 4%
		Relative distance	Long: 87.5%	Moderate: 12.5%	Short: 0
BN6	Ship reduces its speed in a timely manner (PE4)	The stopping ability of the ship	Strong: 1.3%	Medium: 27.2%	Low: 71.5%
		Conditions in the ice channel	Open: 74%	Partially closed: 22%	Closed: 4%
		[a]Alert from the icebreaker	Timely: 100%	–	Not timely: 0
		[#BN3]Lookout (ship)	Sufficient: 87.7%	–	Insufficient: 12.3%

[#BN2], [#BN3] The states of the variables calculated using BN2 and BN3.

[a] The states of the variables are assumed; – State is not defined.

calculation of collision accidents in the Baltic Sea (Zhang et al., 2019). The lookout (BE15) is further modelled by BN3, which is affected by the number of officers on the watch, radar performance, visibility conditions, and crew fitness. There were two officers on the watch, and visibility was recorded in the logbook. The radar failure probability was assumed to be 1×10^{-3} (Xu et al., 2022b). The modelling of the ship crew fitness was analogous to that of an icebreaker crew (see BN1 in Fig. 4). 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 probabilities of the three states of crew fatigue and crew pressure were assumed to be uniformly distributed because of the model's aim of estimating the likelihood of icebreaker–ship collision for the entire voyage. The probabilities of the basic nodes in BN3 are listed in Table 4.

In an escort operation, the assisted ship must always follow the icebreaker's instructions regarding the speed, engine mode, and/or relative distance to the leading icebreaker to maintain a safe distance (Canadian Coast Guard, 2012). However, the icebreaker captain receives information from the assisted ship regarding the technical profile instead of the experience of operating the ship in actual ice conditions. Therefore, wrong/unsuitable orders (BE16) could be obtained from the icebreaker, and the probability was considered to be 8×10^{-4} (Kum and Sahin, 2015). The probability of a curved ice channel (BE17) was calculated based on the degree of the course change. When the course changed by more than 30°, the ice channel was considered curved. The result was 4×10^{-2}, calculated based on the course recording in the AIS data.

In BN4, the ship speed was obtained from the AIS data, whereas the ice environment was calculated based on BN2 (see above). The ship's crew navigation experience and training level were the same as those of BN3. The ice channel conditions were determined based on the icebreaker breadth, relative distance, and ice compression. Icebreaker breadth was regarded as 'large' according to the definition in Table A in the Appendix. Ice compression was regarded as 'low' because the ice along the coastline had melted. The relative distance, D, between the icebreaker and ship was computed based on their respective geographic coordinates using Equation (1), as follows:

$$D = 2R_e \times \sin^{-1}\sqrt{\sin\frac{\Delta lat}{2} \times \sin\frac{\Delta lat}{2} + \cos lat1 \times \cos lat2 \times \left(\sin\frac{\Delta lng}{2}\right)^2} \tag{1}$$

where D denotes the distance between the icebreaker and ship, R_e represents the earth's radius, Δlat represents the difference in latitude between icebreaker and ship, Δlng denotes the difference in longtitude, $lat1$ represents the latitude of ship, and $lat2$ represents the latitude of the icebreaker. The latitude and longitude of the icebreaker and ship were obtained from AIS data.

In BN 5, communication between the crew members on board was presumed to be sufficient because of the homogeneity of the crew members, all of whom were native speakers of the same language. The stopping ability of a ship is primarily determined by its engine power, speed, and draft, as noted by (Harvald, 1976). In this study, we used ship speed as an indicator of its stopping ability, which was classified as low (speed >8 kn), medium (4 kn ≤ speed ≤8 kn), and strong (speed < 4 kn). The alert from the icebreaker in BN 6 was assumed to occur without delay (timely).

4.1.2. Process of CPT determination for BN models

The Røed method (Røed et al., 2009) was used to quantify the relationship between variables (i.e. the CPT) using the exponential functions of the distance between weighted average parent states and child node states. In this method, the weights of the parent nodes and the outcome distribution index R are obtained via a questionnaire. The specifics for determining the CPT for the BN models are as follows:

1. Design a questionnaire. The objective of the questionnaire is to elicit expert opinions regarding the weights of parent nodes and the outcome distribution index *R,* which distributes the probability mass between the possible outcomes. The questionnaire consists of three sections. The first part of the questionnaire aims to acquire the backgrounds of the experts, and the results are shown in Table 5. Part 2 explains how to complete the questionnaire. Part 3 consists of six BNs in which weight and index R-related questions must be answered. The format of the questionnaire is identical to that of Xu et al. (2022b).
2. Calculate the weight and index R. The calculation of weights adheres to the analytic hierarchy process, i.e. construction of the comparison matrix, calculation of the consistency ratio of the comparison matrix, and normalization of the maximum eigenvector. The calculation of index R is based on Equation (2).

$$e^{-S_1 \times R} = (\text{Probability factor }) \times e^{-S_n \times R} \tag{2}$$

where S_1 is the 1st state of the child node, S_n is the nth state of the child node, and the probability factor is calculated according to expert judgment. Calculation details and illustrations can be found in Xu et al. (2022a).

3 Calculate the probability distribution. The CPT is determined using the Røed method, which assumes that the probability of a child node being in a state that differs considerably from its parents' states must be small compared with 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 is the probability that should be assigned. The weighted distance is first calculated using Equation (3), where D_j is the distance between the *jth* state of the child node and the states of all parent nodes, W_i is the weight of the ith parent node, D_{ij} is the distance between the *jth* state of the child node and the *ith* parent node, S_1 is the 1st state of the child node, and S_n is the *nth* state of the child node. Subsequently, the probability distribution of the states of the child node in focus is calculated based on Equation (4), where the numerator term is the probability mass for the *jth* state, and the denominator term provides a normalization factor that causes the sum of the P_js to be equal to 1.

$$D_j = \sum_{i=1}^{n} D_{ij} * W_i \quad where\ \ j \in [S_1, S_n] \tag{3}$$

$$P_j = \frac{e^{-R*D_j}}{\sum_{S_1}^{S_n} e^{-R*D_j}} \ \ where\ P_j \in [0, 1] \tag{4}$$

4.2. Results

According to Section 4.1, the probabilities of the top events of FTs and the target nodes of BN were calculated, and the corresponding probabilities of IEs and PEs are shown in Fig. 6. The probabilities of the end events were calculated based on the ESD. The collision probability of the case study was equal to the sum of the three collision probabilities (Scenarios 1, 3, and 5), which was 6.4×10^{-2}. This probability was an estimate for the entire voyage. In other words, the model expects approximately seven collisions if the escort operation is repeated 100 times under identical conditions.

Table 5
Background of merchant ship captains.

Experts	Position on board	Ice navigation experience/years
E1	Captain	7
E2	Captain	5
E3	Captain	10
E4	Captain	13

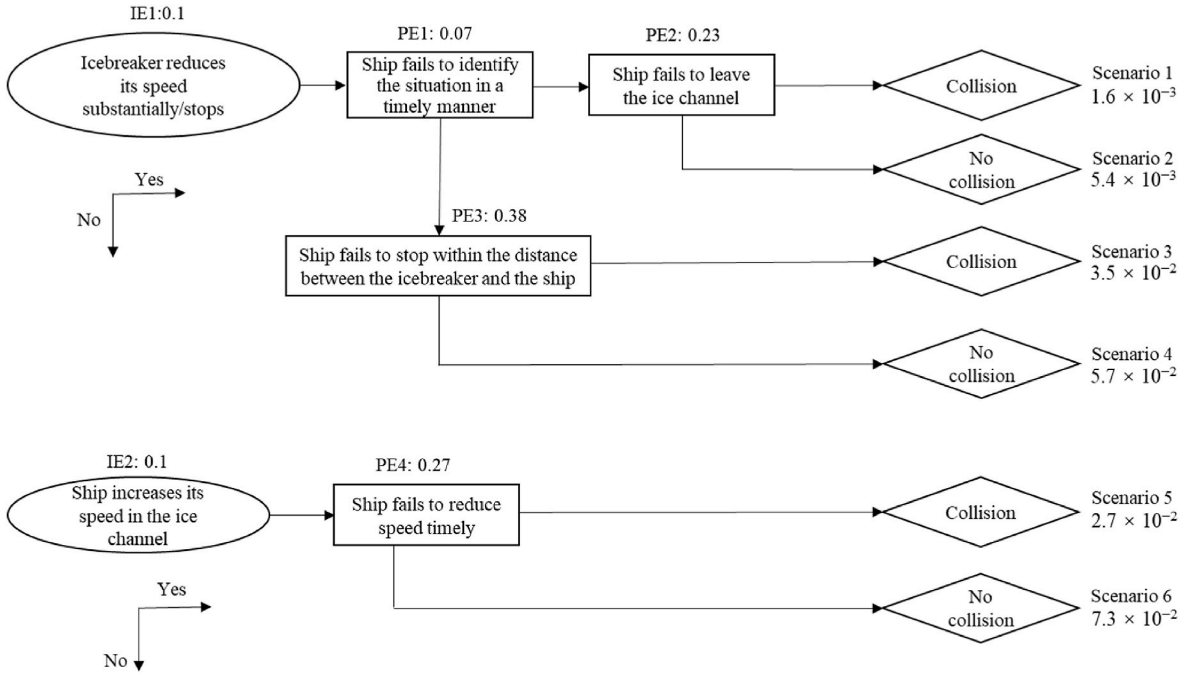


Fig. 6. Results of the case study for the Northeast Passage voyage shown in Fig. 5.

5. Discussion

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

- Model and results analysis
- RCO analysis
- Inspiration for further development of the Polar Operational Limit Assessment Risk Index System (POLARIS)

5.1. Model and result analysis

5.1.1. Qualitative and sensitivity analysis

The objective of the qualitative analysis of FTs is to identify critical events and the best methods to reduce the risk associated with a top event. Qualitative analysis of the FTs was performed by identifying cut sets. The cut set in a fault tree refers to a set of basic events whose simultaneous occurrence leads to the occurrence of a TOP event. The minimum cut set denotes that a cut set is considered to be minimal if it cannot be reduced without losing its status as a cut set (Rausand and Haugen, 2020). The identification of minimal cut sets was performed using the method for obtaining cut sets (MOCUS); for further details, refer to Rausand and Haugen (2020). The results of the qualitative analyses are presented in Table 6. When basic event(s) is/are absent in a minimum cut set, the top event does not occur. Therefore, by obtaining the minimum cut sets, the operator knows which basic events require risk control options (RCOs) to avoid the occurrence of the TOP event. Additional RCOs are discussed in Section 5.2.

The aim of BN sensitivity analysis is to determine how the target node is affected by a small change to the basic node. If a small change in the basic node results in a significant change in the target node, the target node is considered to be sensitive to the basic node. The identification of sensitive nodes enables the end-users of the BN to be aware of the effects of these nodes that contribute to icebreaker and ship collisions. The degree of sensitivity is reflected in the concept of the variation in the probability of the target node (VPTN), which is the absolute difference in 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 (Xu et al., 2022b):

Table 6
Minimum cut sets of FTs.

NO.	Minimum cut set
FT1	{Icebreaker steering system failure}, {Icebreaker engine failure}, {Darkness, Low technical icebreaking capacity}, {Darkness, Severe ice environment}, {Low visibility, Low technical icebreaking capacity}, {Low visibility, Severe ice environment}, {Thick snow covers ice, Low technical icebreaking capacity}, {Thick snow covers ice, Severe ice environment}, {High ice compression, Low technical icebreaking capacity}, {High ice compression, Severe ice environment}, {Lack of updated information, Low technical icebreaking capacity}, {Lack of updated information, Severe ice environment}, {Insufficient crew fitness (icebreaker), Low technical icebreaking capacity}, { Insufficient crew fitness (icebreaker), Severe ice environment}
FT2	{Failure of communication equipment (icebreaker), Insufficient lookout (ship)}, {Failure of communication equipment (ship), Insufficient lookout (ship)}, {Lack of situational awareness (icebreaker), Insufficient lookout (ship)}, {Language misunderstanding, Insufficient lookout (ship)}
FT3	{Wrong telegraph order from icebreaker}, {Ice channel is curved}, {Lack of situational awareness (icebreaker), Insufficient lookout (ship)}

- **Step 1** Set the probability of State 1 (shown in Table 4) of one basic node to 100%, and calculate the probability of one state of the target node.
- **Step 2** Subsequently, set the probability of State 3 (shown in Table 4) of the basic node to 100%, and calculate the probability of the state of the target node, similar to that in Step 2.
- **Step 3** Calculate the VPTN based on the two calculated probabilities of the state of the target node obtained in Steps 1 and 2.

The obtained results are summarised in Fig. 7. The primary findings were as follows:

For the target node 'crew fitness (icebreaker)' (BN1), the most important factor was navigation experience (54%). The other significant factor was the training level, but it was much less significant than the navigation experience. For the target node 'ice environment' (BN2), ice compression and ice ridge were the two most influential factors, each contributing more than 25% to the probability variation. Regarding the

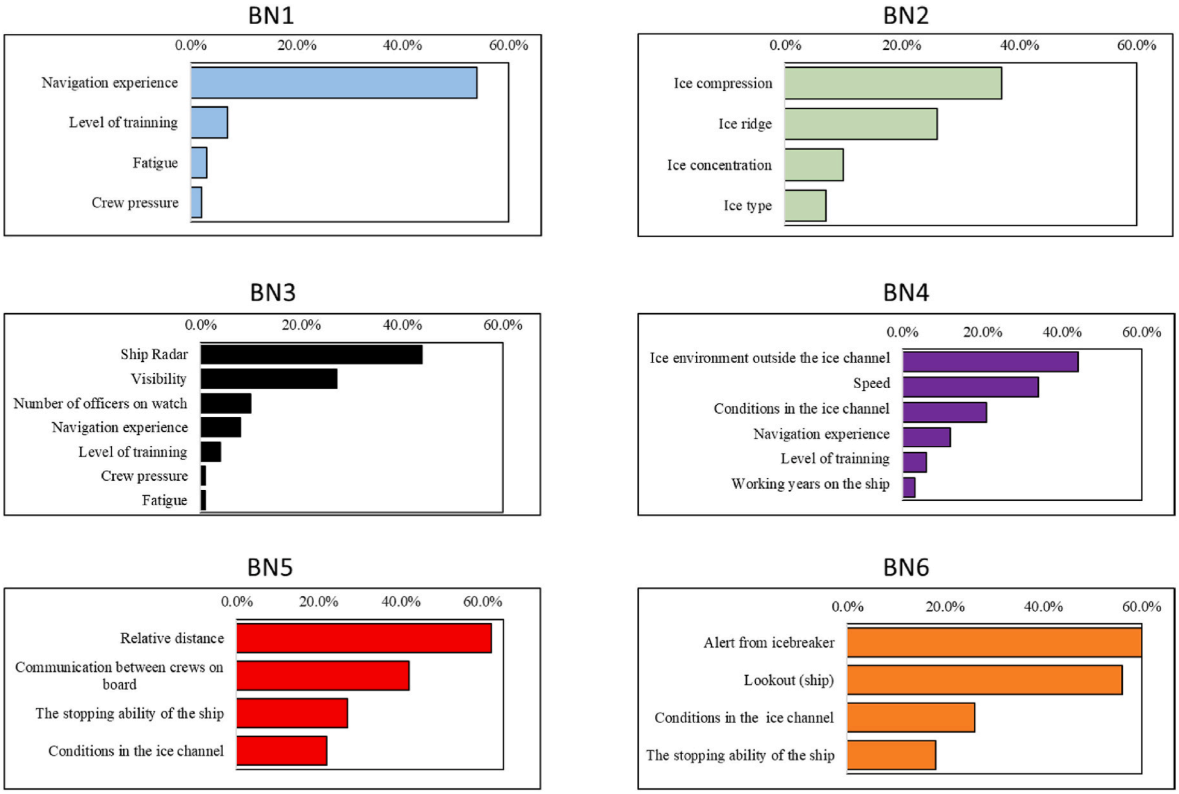


Fig. 7. Sensitivity of each basic node to the target nodes (BN: Bayesian network).

'lookout (ship)' (BN3), the two most important factors were ship radar and visibility. The number of officers on the watch and their navigation experience accounted for approximately 10% of the variation in the lookout (ship) probability. The target node 'ship leaves the ice channel' (BN4) was primarily sensitive to ice environment outside the ice channel. Ship speed and conditions in the ice channel were two important factors affecting the success of a ship leaving the ice channel. Human factors such as navigation experience, level of training, and working years on the ship had less impact on the ship leaving the ice channel. The target node 'ship stops within the relative distance' (BN5) was sensitive to all parent nodes (see BN6 in Fig. 7) (the minimum VPTN was 22%), with the most sensitive node being the 'relative distance' (sensitivity of 62%). Regarding the node 'the ship reduces its speed in a timely manner' (BN6), alerts from the icebreaker and lookout (ship) were the two most important factors.

A comparison of the important risk factors identified in this study with those identified in previous studies is presented in Table 7. According to the comparison, the important factors identified in this study (for the conditions along the Northeast Passage) were in good agreement with those identified for the Baltic Sea. Commonly considered important factors are related to environmental factors (e.g. severe ice environment and poor visibility) and technical factors related to icebreakers and ships (e.g. ship speed and relative distance). In addition, this study identified that the low technical icebreaking of icebreakers and curved ice

Table 7
Important risk factors identified in different studies.

Study	Collision model/approach for the identification of important factors	Identified important factors			Area
		Technical factors related to the ship and icebreaker	Environmental factors	Human and organizational factors	
This study	HCL model Qualitative analysis of FT (minimum cut sets) Sensitivity analysis of BN (VPTN)	1) Icebreaker's low technical icebreaking 2) Ship speed 3) Ship radar	1) Ice concentration 2) Ice ridge 3) Ice type 4) Ice compression 5) Visibility 6) Curved ice channel	1) Alert form the icebreaker 2) Communication between crews on board 3) Insufficient lookout 4) Wrong order from the icebreaker	Arctic
Zhang et al. (2019)	Human factor analysis and classification system Fault tree Statistical analysis Qualitative analysis of FT	1) Ship speed 2) Relative distance	1) Ice conditions 2) Ice ridge 3) Bad visibility 4) Snowy/rainy weather.	1) Improper route selection	Baltic Sea
Franck and Holm Roos (2013)	Accident report investigation	1) Short distance 2) Ship speed	1) Severe ice conditions	1) Communication between icebreaker and ship	Baltic Sea
(Valdez Banda et al., 2015)	Statistical analysis Expert judgment	1) Relative distance	1) Ice ridges 2) Level ice with thicknesses between 0.15 and 0.4 m 3) Low temperatures (−20 to −40 °C).	–	Baltic Sea

channels are also important factors. Regarding human and organizational factors, this study observed that alerts and orders from icebreakers, communication between crews, and lookouts from ships are critical in the Arctic region during escort operations.

5.1.2. Uncertainty analysis of the case study

A case study of the proposed model was conducted based on the evidence recorded in the logbook of Tian Hui, AIS data, and captain-written voyage reports. The uncertainties of the inaccuracies in expert judgment, data, and modelling procedures that may influence the results were considered. The ratings for uncertainty estimation were proposed by Flage and Aven (2009) and applied by Liu et al. (2020) and Zhang et al. (2022)a,b. A brief interpretation of the rating is shown in Table 8, and the uncertainty estimation in this study is presented in Table 9.

5.1.3. Model application and limitations

In Section 4, the applicability of the developed model has been demonstrated through a case study based on data from a real voyage. In addition to the case study, the proposed model can be used to estimate the collision risk of a planned route. By utilising this model, the probability of technical failure, such as ship engine failure, can be referenced in technical documents or literature. The probability of human factors such as crew fatigue can be estimated by the captain/stakeholders according to the crew's working shift. The probability of environmental factors, such as low visibility, can be acquired from the forecast platform, including uncertainties. In addition, the model can reveal the collision risk of each waypoint when the aforementioned input probabilities are accessible. Thus, it can be used to identify the high-risk portion of a voyage and remind the operator to navigate cautiously or alter the route.

However, this model has some limitations applied in the Arctic navigation. From the case study, the input data relied on the provided waypoint record information in the crew's logbook. The input data for the case study has a moderate uncertainty according to the uncertainty analysis in Section 5.1.2. Consequently, the accuracy of the result is highly dependent on the number and arrangement of waypoints along the entire voyage and the quality of the input data. This model only estimates the static probability of icebreaker-ship collision for the entire voyage. With the growing interests in the dynamic risk analysis in the Arctic (Khan et al., 2020; Li et al., 2020, 2021a,b; Li et al., 2021a,b), this model needs some modification to suit the requirements of this mission (e.g., integrating the FT with a binary decision approach, as proposed by Jiang et al. (2021), or. transferring both the FT and ESD into a BN, as suggested by Khakzad et al. (2013)).

The model relies on the input from human experts and its applicability was demonstrated using actual data from one escort transit along the Northeast passage. Once more beset data becomes available, we recommend conducting additional investigations of the model limitations.

5.2. RCO analysis

The aim of this analysis is twofold: to effectively communicate potential hazards associated with specific operations to relevant stakeholders (see below), and to collaboratively develop RCOs for reducing risks (Cheng et al., 2023; Rausand and Haugen, 2020). According to the results of the qualitative and sensitivity analyses, RCOs are proposed from several perspectives: the icebreaker company, shipping company, crew on the icebreaker, and crew on the ship.

Table 8
Interpretation of uncertainty ratings (Flage and Aven, 2009).

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

Table 9
Uncertainty assessment for the case study.

Uncertainty element	Rating	Justification
Input data	Moderate	The input data collected from the logbook, AIS, and voyage summary report are recognized as trustworthy in Section 4.1.1. However, some inaccuracies may exist, as follows: • Owing to a lack of information regarding the icebreaker, the statistics regarding the icebreaker may contain some inaccuracies. • The total number of waypoints (eight) is insufficient to represent an entire journey. Therefore, in the case study, the calculated probability of basic events/nodes based on the waypoints could change if other information becomes available. • The ice thickness derived from the Copernicus data is used to estimate the probability of the 'icebreaker's low technical icebreaking capacity' occurring during the voyage. However, owing to the ice drift, the recorded ice thickness may differ from the actual value. It is recommended to include ice information as a part of the AIS message.
Model	Low	The model and correlation between events/nodes in the model have been validated by four icebreaker captains with extensive ice navigation experience. Therefore, the uncertainty in the model objective and variable correlation is low.
CPT determination	Low	The experts invited to estimate the CPT of BNs were merchant captains from COSCO group with Arctic navigation experience. As a result, the uncertainty in the CPT determination is considered to be low according to the findings by Xu et al. (2022a).

5.2.1. Icebreaker company

Referring to Table 6, 'severe ice environment' and 'low technical icebreaking capacity' are the two primary reasons that the icebreaker reduces its speed significantly or stops (IE1). Therefore, the icebreaker service provider should assign an appropriate icebreaker to escort the ship, and the icebreaker can plot a preliminary route prior to the commencement of the escort operation based on the available ice information (forecasts, etc.) and information about the escorted vessel.

Regarding IE2, the minimum cut sets contributing to ship speed increases in ice channels are {Wrong telegraph order from icebreaker}, {Ice channel is curved}, and {Lack of situational awareness (icebreaker), insufficient lookout (ship)}. An incorrect telegraph order may result from an icebreaker's lack of familiarity with the ship's technical capabilities. Therefore, a practical solution is for an icebreaker service company to provide icebreaker crews with training in the operation of various types of ships. This training can be accomplished by utilising a simulation platform at its full potential.

5.2.2. Ship company

PE2 is sensitive to the ice environment outside the ice channel and ship speed (see Section 5.1). This implies that it is difficult for a ship to leave the ice channel when the ice environment is severe and ship speed is relatively low. Therefore, under these circumstances, the assisted ship may attempt to stop rather than deviate from the ice channel. If the ice environment is not severe, or if the ice contains some leads, leaving the ice channel may be preferable for slowing down. This discovery can be included as part of emergency response guidance in ship companies' training programs.

5.2.3. Crews on the icebreaker and ship

Referring to Section 5.2, relative distance is the most significant factor affecting PE3. Consequently, during escort operations, a safe distance must be maintained between the icebreaker and ship. In actual operation, the assisted ship must obey the icebreaker's commands unless this is in disagreement with the ship's own regulations (e.g. astern movement is not allowed with a conventional propeller) (Canadian Coast Guard, 2012). Furthermore, the assisted ship's captain should estimate a safe distance because he or she is more familiar with the ship's operational capabilities, such as its stopping ability. The ship captain should initiate communication with the icebreaker if the relative distance is too small to stop the ship. The crew should utilise a standard operation order to reduce misunderstandings regarding the ship's operations (IMO, 2001). These commands should be issued with clarity and accuracy. The conditions in the ice channel are also an important factor that affects the stopping distance of the assisted ship (Fig. 7). Therefore, crews on both icebreakers and ships should have some experience with or knowledge of methods to estimate the effect of ice on ship manoeuvrability. This estimation can guide the icebreaker to provide suitable orders related to the relative distance and assist the ship in assessing the risk of collision when the icebreaker stops.

During the escort operation, the icebreaker should attempt to avoid sharp turns based on the manoeuvring capability of the escorted ship. Therefore, the icebreaker should be able to estimate the ice environment as much in advance as possible and make decisions regarding the route beforehand. Finally, icebreakers and/or ships must maintain adequate watchkeeping.

PE1 was modelled using FT2, where the lookout (ship) was the most important factor. The lookout was further analysed using BN3, and the sensitivity analysis is presented in Section 5.1. The icebreaker should make every effort to avoid areas with low visibility, and if this is not possible, it should maintain adequate communication and radar focus. Regarding human factors, icebreakers and ships should assign a sufficient number of watchmen with extensive navigational experience.

5.2.4. Summary

From the ESD in an escort operation (Fig. 6), the event in which the 'ship fails to stop within the distance between icebreaker and ship' (PE3) is the most hazardous event resulting in icebreaker–ship collision, followed by the event in which the 'ship fails to leave the ice channel' (PE2) and the event in which the 'ship fails to reduce its speed in a timely manner' (PE4).

The important factor 'relative distance' can be difficult to control from both the icebreaker's and escorted vessel's perspectives. The icebreaker must consider the effect of ice on the icebreaker and assisted ship, the ship crew's lookout, and the communication between the icebreaker and ship. Accurate ice environments are difficult to forecast, especially in summer when ice drift is present.

This scenario becomes even more complex during convoy operations, as the icebreaker must consider the manoeuvrability/technical characteristics of all the vessels in a convoy. Some of these could be very different from those of icebreakers (e.g. turning radius).

5.3. Inspiration for POLARIS modification

The POLARIS is an approach recommended by the International Maritime Organization (IMO, 2016) for evaluating a numeral (so-called 'risk index outcome') that represents the risk (probably of an accidental event) for a ship with a particular ice class operating in given ice conditions; it is calculated as follows:

$$RIO = \sum_{i=1}^{n} C_i \times RV_i \tag{5}$$

where C_i represents the concentration (in tenths) of ice types within the ice regime (including open water), and RV_i represents the corresponding risk index values, which are functions of the vessel's ice class and stage of ice development. When a ship is assisted by an icebreaker, the calculated RIO should be modified by adding 10 to its calculated value, as recommended by the IMO (2016), thus making an 'accidental event' caused by ice less probable.

Note that the escort operation will decrease the risk (probably of an accidental event) posed by ice but increase the risk posed by icebreakers (i.e., icebreaker–ship collisions). In particular, the presented model shows that when the escort operation is conducted under severe ice conditions and poor visibility, the probability of the icebreaker decreasing its speed significantly (or stopping) increases compared with escort operations conducted under light ice and good visibility conditions. This change is currently not successfully reflected in RIO calculations and requires to be further studied in detail.

6. Summary and conclusive remarks

In this study, a novel hybrid causal logic model was developed to estimate the probability of icebreaker–ship collisions in an escort operation along the Northeast Passage. The model identifies two initiating events ('the icebreaker reduces its speed significantly/stops' and 'the ship increases its speed in the ice channel') that can result in a collision. The applicability of the model was demonstrated using actual data from an escort transit along the Northeast Passage in 2018. Risk control options are proposed based on qualitative and sensitivity analyses of the model. The principal findings are summarised as follows.

- The event 'ship fails to stop within the distance between the icebreaker and ship' is the most hazardous event that results in a collision, and 'relative distance between the icebreaker and ship' is the most significant factor affecting this event.
- Ice compression and ice ridges are the two most important factors that result in the event 'icebreaker reduces its speed significantly/stops', but this ice information (e.g. history of occurrences along a predefined route) is rarely available.
- Lookouts are crucial in escort operations. Among the human factors, the number of officers on watch is the most important factor in lookout operations.
- The ice environment outside the ice channel and ship speed are the two most important factors affecting ships leaving the ice channel.

The results of this study can assist shipping companies to better understand the sequence of events prior to icebreaker–ship collisions during escort operations on ice. This paper provides information underlying the introduction of risk reduction measures.

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.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously and is not under consideration for publication elsewhere, in whole or in part.

Data availability

Data will be made available on request.

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Appendix

Table A
Description of identified nodes for the developed BN model.

Variables	States	Description	Ref.
BN1			
Crew fitness (icebreaker)	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, level of training.	Xu et al. (2022b)
Navigation experience (icebreaker)	Rich, medium, brief	Refers to the operation experience in Arctic areas. Rich: experience >10 years, medium: 5 years $\leq$ experience ≤ 10 years, brief: experience < 5 years.	Xu et al. (2022b)
Crew fatigue (icebreaker)	Severe, moderate, light	Refers to the working hours after the crew took over. Severe: working hours >2.6 h, moderate: 1.3 h $\leq$ working hours ≤ 2.6 h, light: working hours < 1.3 h.	Xu et al. (2022b)
Crew pressure (icebreaker)	High, moderate, low	Refers to the mental pressure that primarily results 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 used 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.	Xu et al. (2022b)
Level of training (icebreaker)	Extra, basic	Refers to the training of operation. 'Basic' implies the crew on board has completed the training required by Polar Code and International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), which 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.	Xu et al. (2022b)
BN2			
Ice environment	Severe, medium, light	The ice environment refers to the ice environment around the icebreaker and ice environment outside the ice channel. 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: thick of ice ≥ 120 cm, such as first-year thick ice, multi-year ice, moderate: 70 cm $\leq$ thick of ice ≤ 120 cm, light: thick of ice < 70 cm.	Xu et al. (2022b)
Ice ridge	Yes, no	The ice concentration is the dominant factors in ice ridging. The frequently quoted threshold for ridging is 0.8. Yes: ice concentration ≥ 0.8, no: ice concentration < 0.8.	Løset et al. (2006)
Ice compression	High, medium, low	The ice compression is primarily caused by an air force (i.e. wind) and water force (i.e. current), and the wind force will dominate the ice drift. However, the ice compression exists when the ice extends to the coastline. The ice compression can be divided into three states indicated by wind speed. High: wind force >8, medium: 4 < wind force ≤ 8, low: wind force ≤ 4.	Leppäranta (2011)
Ice concentration	High, medium, low	Refers to the density of ice in the area. High: density $>70\%$, medium: 30% $\leq$ density $\leq 70\%$, low: density < 30%.	
BN3			
Lookout (ship)	Sufficient, insufficient	Refers to the awareness of the events on the icebreaker and ice channel and assess its 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 cannot determine the problem in time, resulting in delayed action.	Xu et al. (2022b)
Ship radar	Functioning, failed	Refers to the working states of the ship radar.	
Visibility	Good, moderate, low	Refers to the visual distance at which the icebreaker can discern the object and ice conditions on the voyage. Good: distance >4 km, moderate: 1 km $\leq$ distance ≤ 4 km, poor: distance < 1 km.	
Number of officers on watch	Sufficient, insufficient	Refers to the numbers of officers on watch in bridge. Sufficient: 2 $\leq$ number of officers, insufficient: number of officers ≤ 1.	
Crew fitness (ship)	High, moderate, low	Same with 'Crew fitness (icebreaker)'. See BN1	
BN4			
Ship leaves the ice channel	Successful, failed	Refers to whether the ship leaves the ice channel successfully.	
Ice environment outside the ice channel	Severe, medium, light	Same with 'ice environment' in BN2.	
Conditions in ice channel	Open, partially closed, closed	Refers to the ice conditions of ice channel. 'Open' implies an open-water channel in ice field, with the ice fragments cleaned out; 'partially closed' implies that the ice fragments move to the middle of the ice channel, causing the open-water channel to be narrower; 'closed' implies that the ice channel is fully covered by ice fragments.	
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 breadth	Large, medium, small	Refers to the breadth of the icebreaker, which are in service in the Northeast Passage. Large: breadth ≥ 28 m, medium: 22 m $\leq$ breadth < 28 m, Small: breadth < 22 m.	

(*continued on next page*)

Table A (*continued*)

Variables	States	Description	Ref.
Relative distance	Short, moderate, long	Refers to the distance between the bow of the assisted ship and stern of the icebreaker. Short: distance < 1 cable, moderate: 1 cable ≤ distance ≤3 cable, long: distance >3 cable.	
Wind effect	Strong, medium, light	Refers to the wind effect on the close of 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 relationship between the Beaufort scale and wind speed can be found online. Extreme: Beaufort number 9–12 (velocity ≥20.8 m/s), moderate: Beaufort number 5–8 (8.0 m/s ≤ velocity ≤20.7 m/s), calm: Beaufort number 1–4 (velocity ≤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° ≤ angle ≤90°, horizontal direction: 0° ≤ angle < 45°	
Current effect	Extreme, moderate, calm	Refers to the current effect on the close of 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 ≥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° ≤ angle ≤90°, horizontal direction: 0° ≤ angle < 45°.	
Ship speed	High, medium, low	Refer to the speed of the ship. High: >8 kn, medium: 4 kn ≤ speed ≤8 kn, low: speed < 4 kn.	
Crew operation	Sufficient, insufficient	Refers to the quality of crew operating the ship.	
Navigation experience (ship)	Rich, medium, brief	Same as 'Navigation experience (icebreaker)'.	
Working years on this ship	High, medium, low	Refer to the familiarity of the characteristics of equipment on board. High: working years >4 years, medium: 2 years ≤ working years ≤4 years, low: working years < 2 years.	
Level of training (ship)	Extra, basic	Same as 'Level of training (icebreaker)'.	
BN5			
Ship stops within the distance between icebreaker and ship	Successful, failed	Refers to the ship stopping within the relative distance between the icebreaker and ship.	
Communication between crews on board	Sufficient, insufficient	Refers to the communication efficiency between the crews on board. 'Sufficient' implies that cooperative actions are clearly understood. 'Insufficient' implies that the cooperative actions are difficult to understand, which is caused by language, noise, etc.	
Stopping ability of ship	Strong, medium, low	The ship's stopping ability is primarily affected by engine power, speed, draft. In this paper, the stopping ability of the ship is indicated by its speed. Low: >8 kn, medium: 4 kn ≤ speed ≤8 kn, strong: speed < 4 kn.	
Conditions in ice channel	Open, partially closed, closed	See BN5.	
Relative distance	Short, moderate, long	See BN4	
BN6			
Ship reduces speed in a timely manner	Successful, failed	Refers to whether the ship reduces its speed timely.	
Stopping ability of ship	Strong, medium, low	See BN5.	
Conditions in ice channel	Open, partially closed, closed	See BN4.	
Alert from the icebreaker	Timely, not timely	Refers to whether icebreaker provides a timely alert when emergencies occur.	
Lookout (ship)	Sufficient, insufficient	See BN3.	

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