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A framework for quantitative analysis of the causation of grounding accidents in arctic shipping

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ABSTRACT

The melting of Arctic Sea ice has significantly facilitated Arctic shipping. However, such increased shipping has brought about higher maritime accidents in Arctic waters, especially for grounding and fire/explosion accidents. The paper presents a framework for quantitative analysis of the causation of grounding accidents in Arctic shipping by developing an accident map (AcciMap) - Bayesian network (BN) model. First, the potential risk factors for grounding accidents in the Arctic shipping were identified according to 322 maritime accident investigation reports (MAIRs) - 299 global MAIRs of grounding accidents (including 5 in Arctic waters) and 23 MAIRs (except grounding accidents) in Arctic waters and related literature. Consequently, an AcciMap model is developed for describing the evolution of grounding accident scenarios and reflecting the interdependency of the identified risk factors. Then, a probabilistic model is proposed to evaluate the probability and severity of the grounding accident for presenting a convincing justification for risk control options (RCOs). The framework is applied for the quantitative analysis of a cruise ship grounding accident in Arctic waters. Results demonstrate (1) improved understanding of cruise ship grounding risk factors related to government supervision, shipping company management, technical and operational management, unsafe incidents and behaviors, and environmental conditions; (2) quantitative analysis of the evolution of grounding accident and better identification of the critical risk factors; (3) determination of RCOs for risk management in Arctic shipping.

1. Introduction

The world economy relies heavily on shipping [1–3]. With the reduction of Arctic sea ice and the continuous improvement of ship navigation technology [4], the Arctic tourism business in Canada, Russia, Iceland, Norway, and other countries and regions continues to increase [5]. As a result, the number of passenger ships sailing in Arctic waters is gradually increasing [6–9]. In 2015, the volume of ship traffic in the Canadian Arctic was three times higher than in the 1980s, with the most significant increase in volume involving yachts and tourist ships [10,11]. According to the tourism report of Quiquikata City in Greenland [12], some 17,268 tourists visited the Arctic Circle in 2016. Compared with the same period in 2015, the number of cruise passengers traveling in August has increased by 15.6%.

Due to the complex and changeable navigation environment in Arctic shipping, the poor navigation aids, and the lack of crew experience in ice operations in Arctic waters [13], maritime accidents are bound to occur. According to AGCS [14], there were 520 accidents in Arctic waters from 2011 to 2020, of which 89 were grounding accidents. Maritime accidents often lead to severe consequences [15–19]. The unique geographical location of the Arctic and the high level of vulnerability of the Arctic sea routes mainly originate from extreme weather conditions, floating ice, and low visibility [20]. As a result, once a maritime accident occurs, the consequences are highly likely to be severe. Therefore, it is necessary to conduct a risk analysis of ship operations in Arctic waters and propose targeted risk control options (RCOs).

Ship navigation in Arctic waters faces several risks, such as collisions, grounding, becoming stuck in ice, sinking, and fires/explosions. Kum and Sahin [21] used fuzzy fault tree analysis (FTA) and root cause

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analysis to identify human and management risk factors in maritime accidents such as collisions, groundings, and mechanical failures that occurred in the Arctic from 1993 to 2011. Aziz et al. [22] applied bow-tie analysis to identify maritime accident scenarios involving fires/explosions and mechanical failures in Arctic waters. Baksh et al. [23] identified sea ice as the main risk factors in Arctic collisions, sinking, and grounding accidents using the Bayesian network (BN). Ma et al. [20] proposed a framework based on the perspective of resilience and used BN to find that the vulnerability of the Arctic route is relatively high. This is mainly due to inherent vulnerabilities, such as extreme weather, ice and water, and poor visibility. The unique geographical environment of the Arctic means ship operations there face the risks of ship-ice collision and falling into the sea ice. Khan et al. [24,25] and Afenyo et al. [26] used BN to assess the risk of ship-ice collisions and proposed critical risk factors involving weather, ice conditions, human error, navigation equipment, and mechanical equipment. Obisesan and Sriramula [27] used an efficient surrogate model to evaluate the probability of ship-iceberg collisions. Ships sailing in the harsh sea ice environment can easily succumb to ice-trap accidents [21]. Zhang et al. [28], Xu et al. [29] and Montewka et al. [30] used a BN to estimate the probability of becoming stuck in ice, ship-ice collisions, and the possible consequences after such accidents. This information was then used to identify a safe navigation speed in ice conditions. Fu et al. [31,32] used a BN and fuzzy event tree analysis (ETA) to study the risk of significant maritime accidents in Arctic waters caused by ice traps. Ship operations in icy waters often require the assistance of icebreakers. Zhang et al. [33] used a human factors analysis classification system and fuzzy tree analysis to analyze ship collision scenarios under icebreaker pilotage and identified the key factors that induce collision risks in terms of human and organizational factors.

Current research on maritime accidents in Arctic shipping is mainly focused on collisions and ship-ice collisions. As the typical accident scenario in Arctic shipping, grounding has not been fully discussed in the previous studies. And most of the risk management of grounding accidents is developed based on accident statistics and expert knowledge, which do not properly consider environmental risk and have certain limitations [34–36]. So, the modeling and evolution analysis of ship grounding accidents in Arctic waters requires considerable investigation. Besides special environmental factors, human and organizational factors also have an important impact on the occurrence of maritime accidents [37,38]. More than 80% of maritime accidents occur due to errors caused by navigators [39], and seafarers with poor theoretical knowledge are vulnerable to accidents with serious consequences [40,41]. Furthermore, the Arctic waters involve multiple governments and are jointly supervised. The navigation environment and personnel are extremely complex. Therefore, when analyzing the safety of Arctic shipping, human and organizational factors need to be considered. The complexity of government supervision, shipping company management, technical and operational management, unsafe incidents and crew behaviors, and environmental factors affecting grounding accidents in Arctic waters have not yet been fully analyzed. Accident map (AcciMap) [42] is a sociotechnical and evolving analytical system analysis method based on the Rasmussen risk management framework. It is mainly used to analyze the connections among a series of interaction events in an accident, and to study the impact mechanism of the accident from the perspective of a complex system. Akyuz [43] pointed out that AcciMap helps strengthen the graphic analysis of accidents and can be used to identify the causes of maritime grounding accidents.

However, it is difficult to solely use the accident modeling method to quantify the complex Arctic maritime transportation system coupling, dynamics, and human-computer interaction characteristics. BN, as the widely used technique for Arctic accident investigation and risk assessment research, has significant advantages in analyzing the importance of maritime accident factors. For example, Kaptan et al. [44] and Fan et al. [45] used BN to quantitatively assess human factors in maritime accidents. Due to the advantages of the AcciMap for sociotechnical and evolving analytical system modeling, AcciMap can be incorporated with the BN to quantitatively discuss how to find out the cause of the accident and propose effective RCOs to reduce the occurrence of accidents.

The aim of this paper is to propose a framework for quantitative analysis of the causation of grounding accidents in Arctic shipping by incorporating AcciMap and BN. The proposed framework can be used to identify the potential risk factors from five perspectives: government regulation, the ship management company, technical and operational management, unsafe incidents and actions, and environmental conditions. Besides, the evolution of grounding accident scenarios reflects the interdependency of the identified risk factors using the AcciMap model. Furthermore, a BN model is proposed for probabilistic analysis of the grounding accident based on the structure of the proposed AcciMap model, which can be used to propose target risk control options (RCOs) for decreasing the risk of ship grounding in Arctic shipping. The primary feature of the resulting accident model is that it enables the expression of the interdependency of the identified risk factors from five perspectives (government regulation, the ship management company, technical and operational management, unsafe incidents and actions, and environmental conditions). Second, the conditional probability tables (CPTs) of the proposed BN model are quantified by 322 maritime accident investigation reports (MAIRs) - 299 global MAIRs of grounding accidents (including 5 in Arctic waters) and 23 MAIRs (except grounding accidents) in Arctic waters. The model provides an insight into the complex effects of human and organizational factors for grounding accidents in Arctic shipping, so as to propose targeted risk control options (RCOs) for the essential risk factors.

The remainder of this paper is organized as follows. Section 2 introduces the framework for quantitative analysis of the causation of grounding accidents in Arctic shipping, the AcciMap model, and the BN. Section 3 introduces the paper's data sources and details of the data. Section 4 interprets the proposed framework using the Clipper Adventurer grounding accident and analyzes the coupling of accident causes. Section 5 discusses the sensitivity of risk factors in diverse accident scenarios and proposes RCOs for risk management in Arctic shipping. Section 6 concludes this paper by summarizing the research findings.

2. Methods

2.1. AcciMap

The AcciMap model is a graphical accident analysis model based on a Rasmussen six-tier, risk management framework [42], and is used to identify and connect the various levels in social technology systems and to explore the cause and effect of accidents. The AcciMap model can characterize the factors that cause accidents at different system levels. The common factors of multiple interactions related to the decisions and actions of participants at each level of each work system lead to accidents. The interaction between these levels (vertical integration, behavior migration) controls the security and performance of the system. Fig. 1 presents a graphical illustration of how the AcciMap model represents the causal relationship between factors, facilitating analysis of the accident system and determining the interaction between decision-makers at different levels.

Analyzing accidents from a global perspective and background can avoid unfair blame on frontline operators [46,47]. The AcciMap model usually consists of six levels: government policy, regulatory bodies and associations, company management, technical and operational management, processes and actor activities, and equipment and surroundings. Among them, nodes (boxes) represent factors, and directed edges (arrows) represent causality. This was the first systematic model for the study of accidents, and it has been used to analyze accidents in fields including transportation [48–51], aviation [52,53], public health [54–56], and oil and gas drilling [57]. In terms of maritime transportation, Rasmussen and Suedung [58] used this method to analyze the

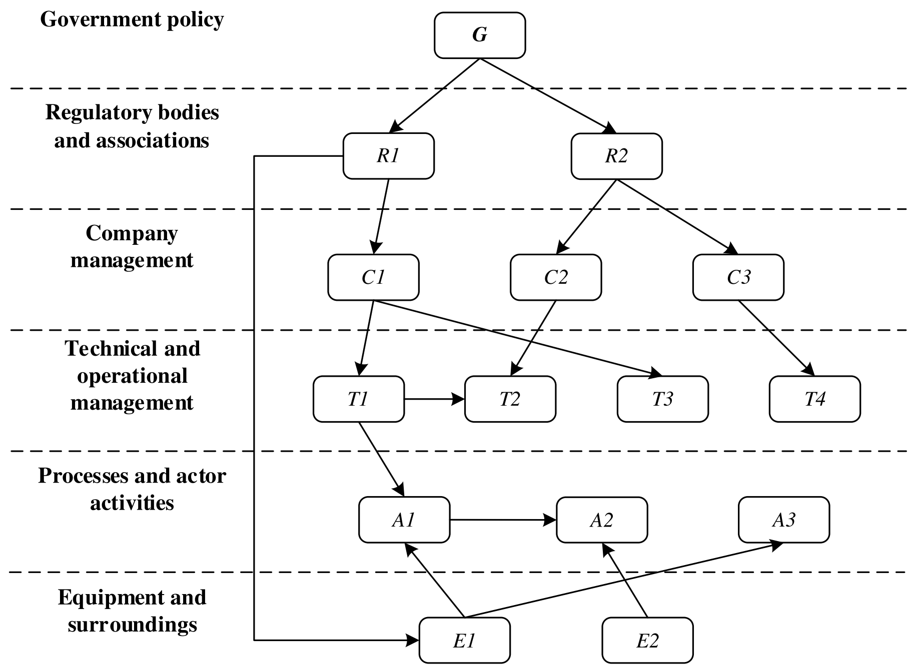


Fig. 1. Graphic representation of AcciMap model.

capsizing accident of the roll-on/roll-off (ro-ro) ship Zeebrügge in 1987, the sinking of the ro-ro ship Vinca Gorthon in 1988, and the grounding accident of the Balina tanker in 1992, and to identify all the organizational bodies that contributed to the creation of these accidents.

2.2. Bayesian network

BN is an uncertainty modeling method that expresses the logical relationship between variables through a probabilistic graphical model [59,60], containing three parts: network node analysis, network structure, and conditional probability transfer between variables, which are used to model the uncertainty in the field or system under consideration.

2.2.1. BN structure

The structure learning of BN refers to determining the topological structure of the BN. The BN expresses a set of random variables and their dependent and independent relationships under their conditions by using a directed acyclic graph (DAG). The DAG is composed of nodes and directed arcs. The node represents a variable element that participates in the consequences of the event, and the directed edge connects the variables represented by each node to express the causal relationship between the variables of different nodes.

2.2.2. BN quantification

BN parameter learning is to determine the conditional probability distribution of nodes in the network under the premise of a given network structure. The directed arcs that connect each node represent the logical relationship between nodes. The strength of the relationship is mainly reflected by CPT. CPT contains all known information about the state of variables. The formula of conditional probability distribution P(V) [61] is as follows:

$$\mathrm{P}(\mathrm{V}) = \prod_{X \in V} P(X|parents(X)), \tag{1}$$

where V means a set of variables (risk factors). $V = \{x_1, x_2, \ldots, x_n\}$ and P be a set of conditional probability distributions of V.

BN can update the probability distribution of each node. The element in the CPT is the state probability of the child node under the parent node state combination, which can be learned by parameter learning on the observation data. BN encodes the joint probability distribution of a set of variables by determining a set of CPT. Each variable is assigned a CPT. CPT describes all the conditional probabilities of all possible combinations of the state of the parent variable. The formulas for conditional posterior probability distribution and joint probability distribution are [61]:

$$\mathrm{P}(X_i = x_i | X_j = x_i) = \frac{P(X_i = x_i)P(X_j = x_j | X_i = x_i)}{p(X_j = x_i)}, \tag{2}$$

$$P(X_i = x_i, X_j = x_j) = P(X_i = x_i)\mathrm{P}(X_j = x_j | X_i = x_i). \tag{3}$$

2.2.3. Inference in a BN

After calculating the CPT of each variable, the BN model can make inferences and reflect changes in node uncertainty in a coherent way. Different variables are combined through causality, and uncertain problems can be effectively solved through the integration and update of information. New information can be provided by setting the node to be analyzed as the target node. Through the transmission of the network, the probability changes of other nodes can be generated, and the degree of influence of related nodes can be found.

2.3. AcciMap-BN

Since AcciMap technique has advantages in graphically representing the system-wide failures, decisions, and actions involved in accidents, using the AcciMap model helps strengthen the graphic analysis of the connections among a series of interaction causes of maritime accidents [62]. BN is often used to facilitate updating and prediction capabilities based on the fault tree and event tree analysis techniques from a case-consequence view of the accident [63–65], which can also be incorporated with AcciMap for quantitative analysis of the causation of grounding accidents in Arctic shipping by considering the potential risk factors from five perspectives: government regulation, the ship management company, technical and operational management, unsafe incidents and actions, and environmental conditions. Besides, systemic risk analysis methods analyze system security by considering functions and interactions. These methods can be divided into two categories:

- Qualitative methods, such as AcciMap, STAMP and FRAM, the final analysis results of these methods may be affected by different knowledge levels of researchers, experience and subjectivity;
- Qantitative methods, such as failure mode and effects analysis, BN, fuzzy. When applying these methods, there is a lot of expert experience information to score risk factors, but the expert's scoring information can be ambiguous and difficult to deal with. Furthermore, many situations cannot be clearly represented in probabilistic form [66].

In order to overcome the above limitations, this paper adopts the systematic risk analysis method of Accimap-BN to analyze the risks of Arctic shipping. AcciMap is used to study the formation mechanism of grounding accidents in Arctic shipping and then analyze the factors leading to grounding accidents and the coupling process between the factors, based on the target maritime accident. Over the past decade, BN has been identified as a powerful tool for human reliability analysis [67]. The AcciMap model is used as the BN structure for grounding accidents analysis, and the CTPs of the BN model is required from the MAIRs. The key risk factors can be better quantitatively analyzed by further research on the model that has been developed by BN, to propose target RCOs.

2.4. Framework

In the context of shipping management, grounding accidents, and Arctic-environment characteristics, combining the Rasmussen risk management framework, AcciMap model and BN allows a grounding accident scenario evolution analysis framework to be proposed. Fig. 2 shows the four main research steps.

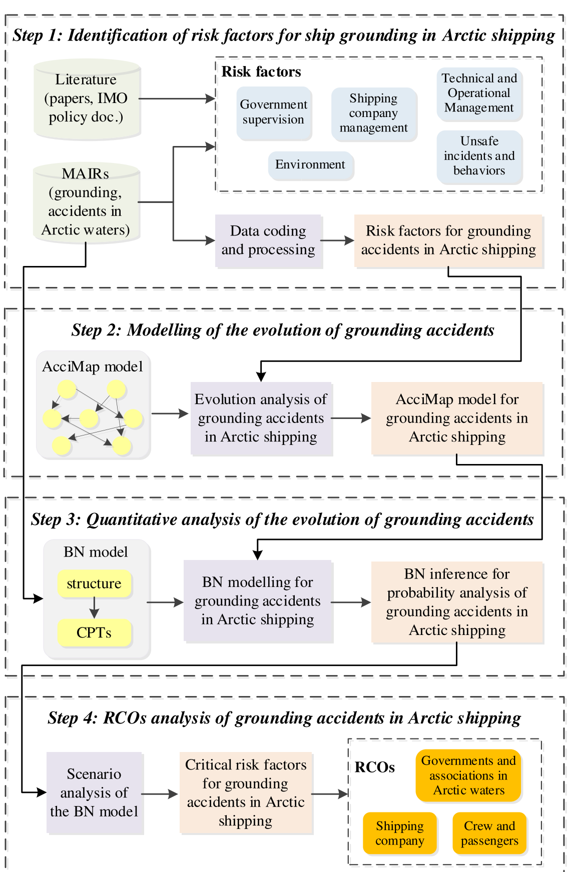


Fig. 2. Framework for quantitative analysis of the causation of grounding accidents in Arctic shipping.

Step 1: Identification of the causes of grounding accidents in Arctic shipping. An in-depth investigation of maritime accident investigation reports (MAIRs) and related literature (including International Maritime Organization (IMO) policy documents) is conducted to establish the specific causes of grounding accidents in Arctic waters, and to establish the impact of related factors, such as government regulation, the ship management company, technical and operational management, unsafe incidents and actions, and environmental conditions, on grounding accidents in Arctic shipping.

Step 2: Modelling of the evolution of grounding accidents in Arctic shipping. Under the process of Step 1, a five-layered framework based on the AcciMap is proposed to describe the complex relationship between the risk factors and accident evolution. It will clearly show the various risk factors involved in accidents and the complex relationships among them.

Step 3: Quantitative analysis of the evolution of grounding accidents in Arctic shipping. In this step, a BN model of the grounding accident is developed based on the proposed AcciMap model under Step 2. The MAIRs are used to calculate the CPTs in the BN model. The probability and associated severity of the grounding accident is evaluated by BN inference. The BN model is also validated by sensitivity analysis.

Step 4: RCOs analysis of grounding accidents in Arctic shipping. Under the analysis of the evolution of a grounding accident in Step 3, this step analyzes the causes of accidents, quantitatively calculates each risk factor's importance by scenario analysis, and proposes targeted risk control measures to reduce accident risk factors and improve navigation safety in Arctic shipping.

3. Data processing

MAIR is a significant data source for maritime safety analysis, recording the involved ships, the details of maritime accidents, and the detailed causes of the accidents. Therefore, we investigated 322 MAIRs, and the data source for these MAIRs is shown in Table 1, and the detailed information of these accidents is listed in Appendix A.

Since we focus on the influences of the coupling of various risk factors on maritime accidents, the analyzed MAIRs should comprehensively record the environmental, ship equipment, human and organizational, factors. 299 global MARIs for grounding accidents (including 5 grounding accidents in Arctic waters) were obtained by searching various maritime databases, including Australian Transport Safety

Table 1.
Data source for the 322 MAIRs.

Source	Number	Link
Marine Accident Investigation Branch (MAIB)	100	https://www.gov.uk/government/organisations/marine-accident-investigation-branch
Shanghai Maritime Safety Administration of PRC (SMSA)	58	https://www.sh.msa.gov.cn/sgdc/index.jhtml
Transportation Safety Board of Canada (TSB)	57	https://tsb.gc.ca/eng/incidents-occurrence/index.html
Australian Transport Safety Bureau (ATSB)	40	https://www.atsb.gov.au/publications/safety-investigation-reports/
Transport Accident Investigation Commission (TAIC)	39	https://www.taic.org.nz/inquiries
National Transport Safety Board (NTSB)	13	https://www.ntsb.gov/investigations/AccidentReports/Pages/Reports.aspx
The Accident Investigation Board Norway (AIBN)	6	https://infogalactic.com/
Danish Maritime Accident Investigation Board (DMAIB)	5	https://dmaib.com/
IMO	3	https://www.imo.org/
MSIU (Marine Safety Investigation Report)	1	https://www.mot.gov.sg/about-mot/transport-safety-investigation-bureau/msib/investigation-report/

Bureau (ATSB), Marine Accident Investigation Branch (MAIB), Maritime Safety Administration (MSA), National Transport Safety Board (NTSB), Transportation Safety Board of Canada (TSB), Transport Accident Investigation Commission (TAIC).

The Arctic MAIRs were collected from the comprehensive maritime database of the eight Arctic countries and the IMO, and the accident location was selected as the Arctic waters, and the MAIRs were obtained from the Global Integrated Shipping Information System (GISIS), TSB, the Danish Maritime Accident Investigation Board (DMAIB) and the Accident Investigation Board Norway (AIBN), combined with the ship accident data collected by Lloyd's Maritime Information Service (LMIS) to double-check the accident information, and obtained a total of 28 MAIRs in Arctic waters. Therefore, excluding 5 duplicate grounding accident reports in Arctic waters, a total of 322 MAIRs were obtained as the sample.

We identify the potential risk factors of grounding accidents in Arctic shipping by comprehensively searching related literature and IMO Resolution A.1075(28) [68]. Then, we code and make a data mining of the potential risk factors from the 322 MARs. Subsequently, we conduct a statistical analysis to obtain the frequency of each risk factor. Through the statistical analysis of risk factors, it provides data sources for subsequent CPT calculations, and calculates the severity of accidents caused by each risk factor. The process of data coding mainly includes:

- Collecting and screening risk factors from the literature;
- After determining the risk factors, an in-depth study of each MAIR, coding the factors into a database (1 means the accident contains the risk factor, 0 means the opposite);
- Count the status of risk factors corresponding to each MAIR, and provide an objective basis for CPTs calculation.

After the in-depth mining of the 322 MAIRs, the mutual risk factors of grounding accidents are identified and ranked from 299 MAIRs of global grounding accidents, as shown in Table 2. In addition, the particular risk factors in Arctic waters are identified from 28 MAIRs in Arctic waters, as shown in Table 3.

4. Case study

4.1. Accident description

A grounding accident scenario analysis framework based on AcciMap is applied to the grounding accident of the ship Clipper Adventurer in Arctic waters. As shown in Fig. 3, from August 14 to August 27, 2010, the Clipper Adventurer cruise ship performed an Arctic cruise during which a grounding accident occurred:

- On August 27, 2010, the Clipper Adventurer left Port Epworth. About 1.5 h later, the ship ran aground on a shoal at 67°58.2′ N, 112°40.3′ W and listed 5° to port. The ship was grounded on a hard rock shelf from approximately the forepeak to amidships.
- Soon after the ship ran aground, the captain contacted an external rescue team for urgent assistance.
- The Joint Rescue Coordination Center (JRCC) was advised of the grounding and initiated an Enhanced Group Calling (EGC) SafetyNet broadcast with distress priority for a 200-mile radius around the Clipper Adventurer. However, the broadcast was stood down when the captain advised that the vessel was not taking on water and was in no immediate danger.
- Within a few hours of the grounding, the captain tried to float the ship twice but failed. At 22:00 local time, the Amundesn ship of the Canadian Coast Guard Service (CCGS) arrived at the scene to transfer passengers.
- On September 1, 2018, the shipping company hired a salvage company to work at the accident site. In the following days, the salvage company continued to carry out rescue activities. Due to adverse weather, the rescue operation failed. On September 14, when the weather further deteriorated, four ships finally rescued the Clipper Adventurer from the shoal. Subsequently, the Clipper Adventurer safely docked at Port Epworth.

Table 2.
Mutual risk factors of grounding accidents (including the grounding accidents in Arctic waters).

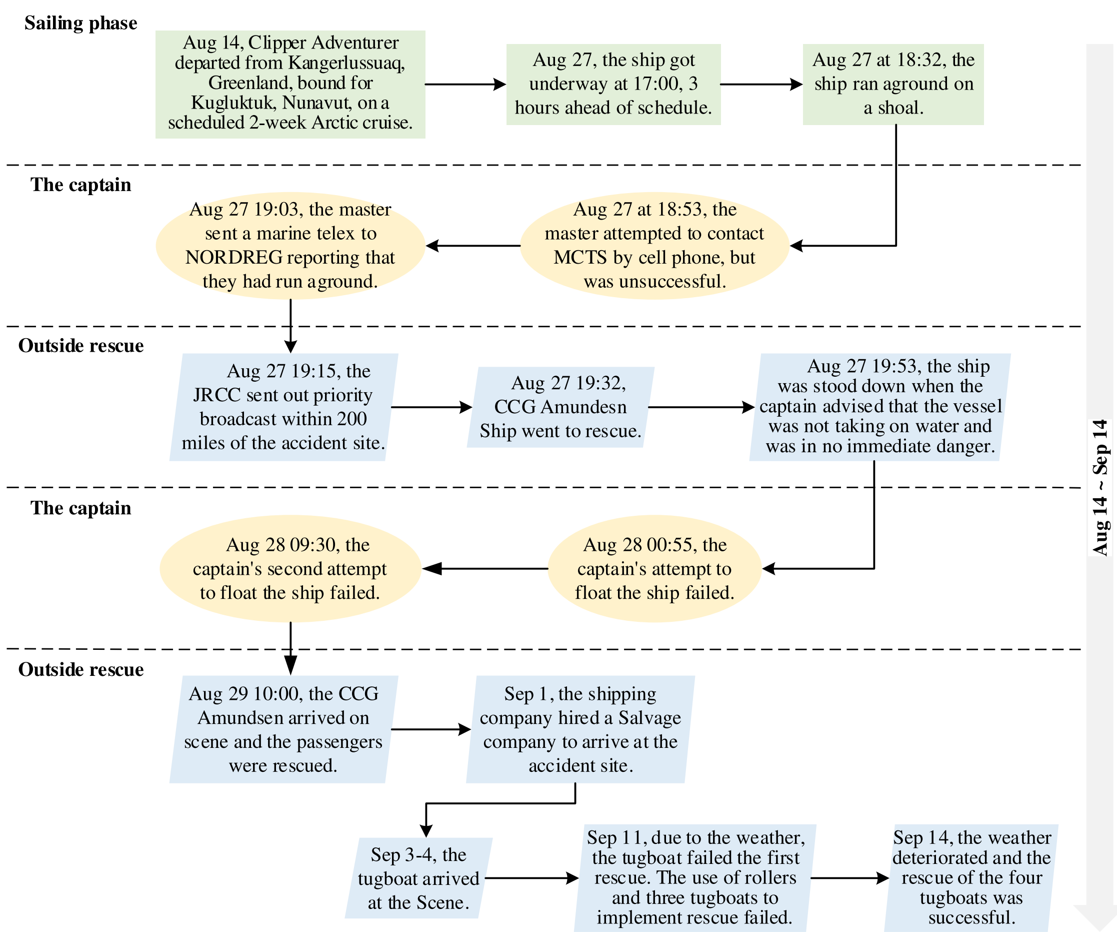
Ranking	Risk factor	Frequency	Percentage	Reference
1	Bad Weather	82	27.42%	[26,69]
2	Irregularities	73	24.41%	[70]
3	Wave	65	21.74%	[21,71]
4	Poor traffic conditions	57	19.06%	[31]
5	Lack of training	54	18.06%	[72]
6	Improper operation	53	17.73%	[21]
7	Fatigue	52	17.39%	[68,73]
8	Wrong decision	46	15.38%	[25]
9	Insufficient communication and collaboration	43	14.38%	[74]
10	Poor lookout	40	13.38%	[73]
11	Improper route planning	39	13.04%	[25]
12	Inexperienced crew	38	12.71%	[75]
13	Off course	37	12.37%	[73]
14	Poor safety management	34	11.37%	[76]
15	Imperfect emergency response	33	11.04%	[77]
16	Poor situational awareness	33	11.04%	[33]
17	Insufficient supervision	32	10.70%	[72]
18	Unupdated chart data	31	10.37%	[23]
19	Misjudgment	21	7.02%	[33]
20	Lack of navigation equipment	20	6.69%	[21]
21	Unsafe speed	19	6.35%	[26]
22	Insufficient preparation for sailing	16	5.35%	[76]
23	Inefficient use of navigation equipment	16	5.35%	[78]
24	Psychological factors	15	5.02%	[76]
25	Underestimate the risk	13	4.35%	[75]
26	Low visibility	12	4.01%	[21]
27	Ship Safety Management System (SMS) conflict	10	3.34%	[72]
28	Unclear division of labor	9	3.01%	[72]
29	Dependent equipment	8	2.68%	[77]
30	Poor external communication	7	2.34%	[73]

Table 3.
Particular risk factors in Arctic waters.

Rank	Risk factors	Frequency	Percentage	Reference
1	Limited information dissemination channels	16	57.14%	[79]
2	Outdated data	14	50.00%	[77]
3	Unreasonable planning and arrangement	11	39.29%	[79]
4	Insufficient work plan	9	32.14%	[80]
5	Poor service quality	9	32.14%	[77]
6	Inconsistent standardization and language	6	21.43%	[81]
7	Improper labeling of the chart	6	21.43%	[77]
8	Improper supervision system, rules and regulations	5	17.86%	[82]
9	Ice	5	17.86%	[83]
10	Poor communication at high latitudes	3	10.71%	[79]
11	Lack of safety management system	3	10.71%	[77]

4.2. Identification of the causes of grounding accidents in Arctic shipping

Because of the characteristics of shipping management and grounding accidents, the six-tier Rasmussen risk management framework was revised to five levels: government supervision, the ship management company, technical and operational management, unsafe



. 3. Clipper Adventurer grounding accident.

incidents and behavior, and environmental conditions. Government policy and supervision agencies and associations are merged into government supervision (level one). These five levels are combined with the natural environment in Arctic waters, comprising climate, temperature, geographic location, and the complex social-environmental characteristics of the governments of eight countries, to produce the system components of each level. Then 34 risk factors were identified based on components combined with accident reports and literature. Table 4 outlines the various factors and their specific causes in the grounding accident of the Clipper Adventurer.

4.3. Analysis of the evolution of grounding accidents in Arctic shipping

Based on a causation analysis of the grounding accident of the Clipper Adventurer, and on the five levels of government supervision, the ship management company, technical and operational management, unsafe incidents and behaviors, environmental factors, AcciMap was used to construct the Clipper Adventurer ship accident. The accident evolution model is shown in Fig. 4.

4.3.1. Government supervision

The cause of the Clipper Adventurer grounding accident lay not only in the actions of the captain and crew, but, notably, in the lack of government supervision. In 2007, the CCG's ship discovered the shoal and reported it to the Canadian Hydrographic Service (CHS). The depth surveys conducted by the CCG were, however, not up to CHS standards based on those of the International Hydrographic Organization (IHO) mentioned in the accident investigation report. Thus, CHS used the term "Notice to Shipping" (NOTSHIP) to warn mariners of local navigation hazards and did not change the chart. However, NOTSHIP is only used in Canada, and the receiving channels of NOTSHIP are not stable. It is impossible to ensure that all international ships are aware of the NOTSHIP warning. CHS did not promptly investigate the shoal or publish chart corrections.

4.3.2. Shipping company management

Poor management of shipping companies is also a significant cause of grounding accidents. Since July 1998, cruise management companies have had to comply with the International Safety Management (ISM) regulations, and assess ship navigation risks. When a ship completes a voyage planning form, the navigation officer should ensure the chart's validity and local navigation warnings are obtained. The shipping company of the Clipper Adventurer relied on the experience and capabilities of the bridge team and did not participate in the revision of the voyage plan, resulting in the ship choosing a route with unknown risks.

The shipping company did not identify all the risks associated with navigation in unknown waters—the specific procedures and guidelines for operating in the Arctic region had not been formulated, and the relevant safety management manuals did not include specific operations for safety-critical equipment. This resulted in a failure to ensure that ships passed at low speed when navigating uninvestigated waters. Moreover, while it was known that the front sonar of the Clipper Adventurer was damaged, the shipping company did not provide any safeguards, repairs, and portable echo detection at the front of the ship, which is generally required when navigating unexplored waters.

4.3.3. Technical and operational management

The Clipper Adventurer grounding accident investigation report revealed some problems in the technical and operational management of the bridge crew (including the captain). First, the bridge team did not

Table 4.
Risk factors analysis of the Clipper Adventurer grounding accident.

Type	Components	Encode	Risk factors	Specific cause
Government supervision	Local government planning	G1	Inconsistent standardization and language	“Notice to Shipping” (NOTSHIP) is only used in Canada, and most foreign ships use the words “local warning” or “navigation warning”
		G2	Poor communication at high latitudes	The Internet is unstable north of 60°N, which restricts online access to the CCG website
		G3	Limited information dissemination channels	NOTSHIP can only be obtained through HF Narrow Band Direct Printing (HF-NBDP) as an alternative to Inmarsat-C, broadcast on NAVAREA 5/10, specific access to Marine Communications and Traffic Services (MCTS), and through logging on to the CCG website
		G4	Unreasonable planning and arrangement	The Canadian Hydrographic Service (CHS) does not have a ship that specifically inspects shoals, and can only investigate them when it is consistent with the CCG’s ship voyage plan and location during the summer voyage
		G5	Insufficient work plan	In 2009, the CHS was prepared to investigate the shoal, but because there was no opportunity to use CCG’s ships, the operation was put on hold
	Regulatory bodies and associations	G6	Improper supervision system, rules and regulations	When the shoal first occurred by the CCG’s ship in 2007, MCTS issued a NOTSHIP. But the sea chart was not permanently modified because its investigation report did not meet International Hydrographic Organization (IHO) standards
		G7	Improper labeling of the chart	To avoid the use of Position Approximates (PAs) and Position Doubtfuls (PDs), the CHS did not modify PAs or PDs in a Notices to Mariners (NOTMAR) manner following IHO standards
		G8	Lack of safety management system	The CHS solely relies on NOTSHIP for navigational warnings regarding shoals, NORDREG did not issue to vessels the written NOTSHIPs applicable to their routes, however, all active NOTSHIPs are available via the Internet
	Government policy	G9	Poor service quality	NAVAREA, as the World-Wide Navigational Warning Service (WWNWS), belongs to the Initial Operating State (IOC), CCG does not guarantee service and availability
		G10	Outdated data	Less than 10% of Arctic Canadian waters have been surveyed by modern technology, and most of the surveyed areas are common routes
Shipping company management	Corporate culture	S1	Unclear division of labor	The ship management company had formulated a Quality, Safety, and Environmental Management System (QSEP) and relied on the captain and the bridge team to follow the guidelines. However, the shipping company did not participate in the revision of the sailing plan
		S2	Lack of training	The ship management company did not ensure that ships pass at a low speed when waters have not been fully explored
	Safety system management	S3	Poor safety management	The ship management company failed to detect damage to the forward-looking sonar and violated the established QSEP guidelines
		S4	Irregularities	The ship management company knew that the forward-looking sonar was damaged but did not give the bridge team safeguard measures
		S5	Underestimate the risk	The ship management company did not identify all risks in unclear waters
		S6	Insufficient supervision	The ship company management did not guarantee that the ship would obtain the local NOTSHIP
		S7	Insufficient communication and collaboration	The ship company management did not know whether the captain was carrying out rescue operations after a comprehensive assessment of the hull
Technical and Operational Management	Operational management	T1	Psychological factors	The captain has sailed on a single-sounding line for many years without accidents and has much experience in Arctic navigation. He was overconfident of the chosen speed and route
		T2	Insufficient preparation for sailing	Not looking for NOTSHIP when planning a route and during a voyage
		T3	Ship SMS conflict	The voyage plan did not meet the requirements of the ship management company
		T4	Improper route planning	The ship’s bridge team chose an under-investigated route
	Technical standard	T5	Unupdated chart data	The shoal was not marked on the latest chart; the updated data on the chart only had NOTMAR, not NOTSHIP
Unsafe incidents and behaviors	Shipping stakeholders	U1	Dependent equipment	Ships rely on echo sounders to monitor the accuracy of chart detection
		U2	Lack of navigation equipment	One or more portable echo sounders was not equipped at the front of the ship
		U3	Imperfect emergency response	The rescue helicopter sent by the JRCC was stood down after hearing the report from the ship. All rescue broadcasts released by MCTS have been suspended
	Crew traits and characteristics	U4	Wrong decision	The captain chose an unreasonable route and speed
		U5	Unsafe speed	The captain sailed at full speed in an incompletely explored route
		U6	Poor situational awareness	No shoal was found
		U7	Improper operation	the chief officer marked 66 m on the icon, whereas the actual depth was 40 m
		U8	Inefficient use of navigation equipment	The ship was equipped to receive all broadcast equipment, and NOTSHIP was not noticed while sailing
		U9	Poor external communication	The crew reported to the rescue center that there was no immediate risk of flooding
		U10	Misjudgment	the crew reported damage to seven cabins, but the actual number was 13
Environment	Channel conditions	E1	Poor traffic conditions	Shoals on the route
	Weather and sea ice conditions	E2	Bad Weather	West wind level 9 and gust level 10

follow the safety requirements of the ship management company when formulating the voyage plan; in fact, there were two alternative sea routes that could be reached in the time mentioned in the accident investigation report, but the master and the bridge team abandoned two routes that had previously been fully investigated. They chose the route that had the shortest voyage time, but one which had not been fully investigated (a shoal existed). Second, the most up-to-date chart—No. 7777 (without NOTSHIP)—aboard the ship did not possess information relating to the shoal. Finally, during the voyage, the bridge team knew that the route had not been fully investigated, but they did not actively

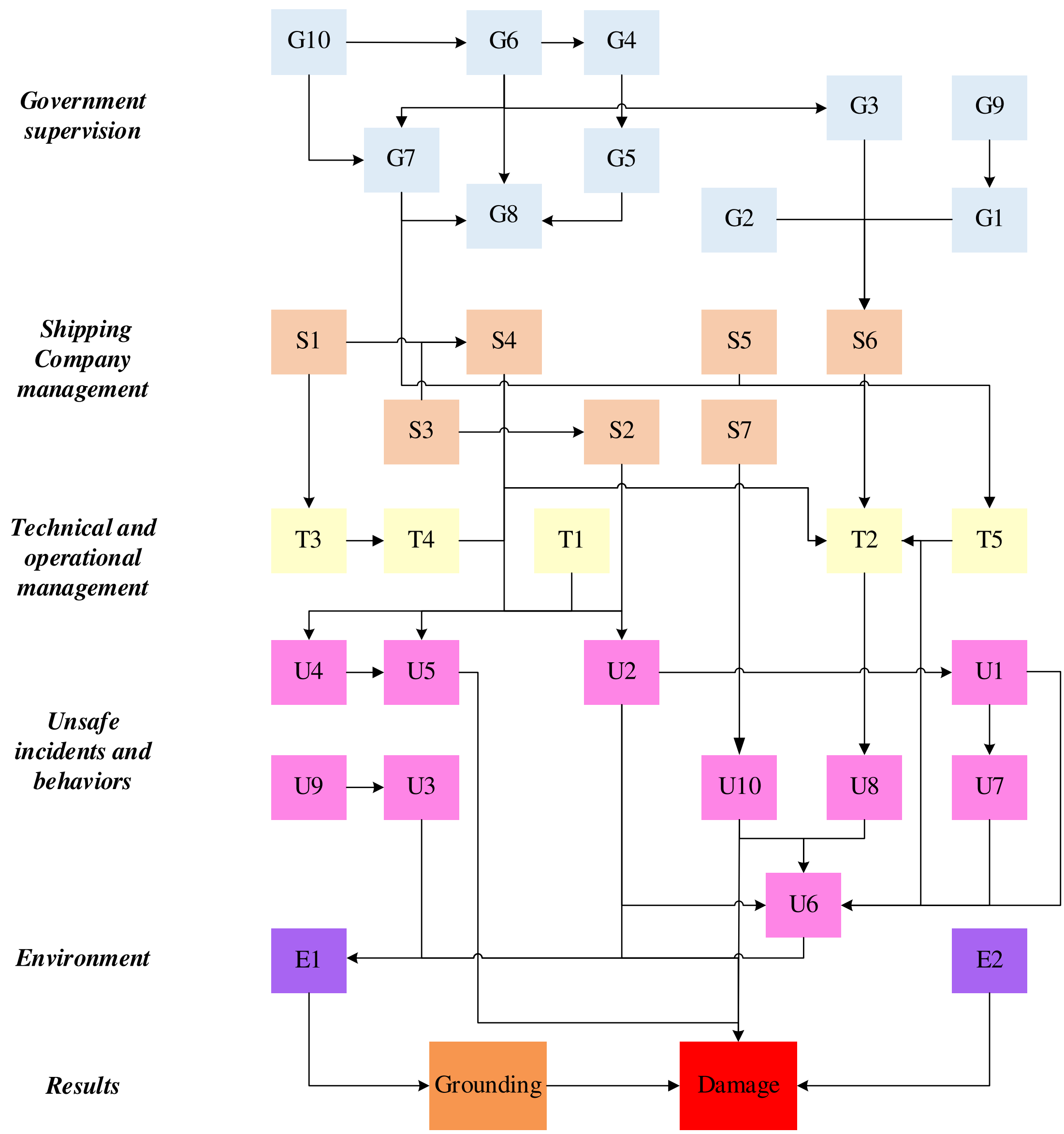


Fig. 4. AcciMap model for the Clipper Adventurer grounding accident.

look for possible dangers along the route, which led to the grounding accident.

4.3.4. Unsafe incidents and behavior

A number of studies have shown that human error is one of the most critical factors in maritime accidents [37,39,45]. Therefore, during the voyage of the ship, it is necessary to focus on the behavior of the crew. The Clipper Adventurer grounding accident investigation report shows that the ship was equipped to listen to the Marine Communications and Traffic Services (MCTS) broadcast navigation warning NOTSHIP messages. When the crew reported the voyage plan to Northern Canada Vessel Traffic Services Zone Regulations (NORDREG), they learned that NOTSHIP messages could be obtained from the Internet, but the crew did not look for any navigational warnings during the voyage. Due to damage to the ship's forward-looking sonar and the absence of a portable echo sounder at the front of the ship, the bridge team could only rely on the accuracy of the sounder monitoring icon detection on the ship. The captain chose to sail at full speed (13.9 kn), but the ship could actually sail at 6 kn and still arrive at the destination on time. This increased the risk of the ship washing up on unknown shallows. After the grounding accident, the crew reported to the shipping company that seven cabins were damaged, but the actual number was 13. The shipping company was not made aware that the captain rushed to implement immediate rescue operations, which resulted in the ship management company not implementing reasonable rescue operations, delaying the rescue of the ship.

4.3.5. Environment

The Arctic water environment is complex, and the captain rashly chose an under-investigated route, which was the main cause of the accident involving the Clipper Adventurer ship. When the Amundesn ship was rescued, the wind reached 9 westerly and gust 10, which further delayed the rescue time and increased the friction between the hull and the shallows, damaging the hull.

The AcciMap model constructed in Fig. 4 provides a global perspective that illustrates the coupled relationships among these events and their related decisions. This elucidates the dependencies among the various factors of the accident and its evolution.

In analyzing the cause of the Clipper Adventurer grounding accident, it is not only necessary to consider the unsafe behavior of the crew on the day of the accident and the related unsafe events, but also to investigate the role of the management company and higher-level factors or external factors. Fig. 4 shows how the AcciMap method enables analysts to identify high-level factors related to organizational, government, and regulatory practices, and to identify the direct causes of the accident. For example, one direct influencing factor in the Clipper Adventurer grounding accident is that no ship had previously established the position of the shoal. This meant that the ship rushed toward the shoal at full speed. Using AcciMap analysis, it is possible to track all factors that led to the failure to identify the location of the shoal.

The sea chart did not show the location of the shoal, and NORDREG did not proactively provide navigation warnings. This resulted in the ship management company's failure to obtain NOTICE for the ship. This directly prompted the Clipper Adventurer bridge team to plan and sail without finding the warning on the broadcast. Therefore, on the day of the accident, the Clipper Adventurer did not have any information about the shoal, despite it having been reported to the CHS, causing the ship to rush onto the shoal while sailing at full speed, and a grounding accident occurred. In its ability to examine the relationships among the factors, as shown in this case, the AcciMap method is a powerful tool for tracking and analyzing the impact factors of different levels of accidents.

The AcciMap model of the Clipper Adventurer grounding accident in Fig. 4 identifies the events and conditions that ultimately led to the grounding accident in the severe environment (west wind 9 and gust 10). This provides a global perspective that illustrates the coupled relationships among the events. This, in turn, elucidates the dependencies among the various factors that caused the accident and the evolution of the accident.

4.4. *Quantitative analysis of the evolution of grounding accidents in Arctic shipping*

Based on the proposed AcciMap model for the Clipper Adventurer grounding accident (shown in Fig. 4), a BN model is further proposed for probabilistic analysis of the grounding accident in Arctic shipping. The nodes and model structure are in accord with the AcciMap model. The CPTs of each node in the BN model are calculated according to the encoded dataset from the 322 MAIRs. The detailed CPTs for the BN model are listed in Appendix B. For example, the CPTs for U6 in the BN model are calculated as the corresponding data from U4, S3 and U6, as shown in Table 5.

According to the CPTs in Appendix B, the edge analysis of each node of the BN model of ship grounding accidents in Arctic waters can be obtained after Bayesian inference. When the probability of a ship being grounded is 100%, the marginal probability of further serious damage is {(no. 0.63), (yes,0.37)}, as shown in Fig. 5. It means that under the environmental conditions and ship conditions shown in Fig. 5, the probability of further damage to the ship is 37%, when the ship is grounding.

A useful means to examine the validity of the BN model is to perform sensitivity analysis, whereby it is possible to graphically analyze the most significant impact of a set of variables on a selected (target) node [24].

Fig. 6 is a tornado diagram of the full range of sensitivity analysis of the BN model when the ship grounding is the target variable of the sensitivity analysis. The length of the bar indicates the extent of the impact of this condition on the ship grounding accident in the Arctic waters. The figure only shows the 10 condition states that have the greatest impact on the ship grounding incident, of which the most influential are poor condition, poor situation awareness and lack of navigation equipment.

Table 5.
The CPTs for the U6 in the BN model.

Node		U4 State = No		U4 State = Yes	
		S3 State = No	S3 State = Yes	S3 State = No	S3 State = Yes
U6	State = No	0.959821	0.931034	0.853659	0.6
	State= Yes	0.040179	0.068966	0.146341	0.4

Fig. 7 shows the tornado diagram of the full range analysis of the sensitivity of the BN model when the ship is further seriously damaged as the target variable of the sensitivity analysis after the ship is grounded. The most influential ones are imperfect emergency response, misjudgment, lack of navigation equipment, and bad weather.

5. Discussion

Due to the occurrence of grounding accidents affected by each level's interaction, we further analyze the critical risk factors in each level by scenario analysis in the proposed BN model. Then, the corresponding RCOs for the critical factors are proposed to reduce grounding accidents in Arctic shipping.

5.1. *Scenario analysis*

The following is the sensitivity analysis of output variables at different scenarios(levels) in the proposed BN model for grounding accidents in Arctic shipping.

5.1.1. *Government supervision sensitivity analysis*

The sensitivity analysis of output nodes under the influence of the first-tier government regulatory factors is shown in Fig. 8.

The degree of influence obtained through the sensitivity analysis is expressed in the shade of the color. It can be seen from the Fig. 8 that when the node (variable) S5 between the government level and the next level is used as the target for sensitivity analysis, the important effects are G1, G3, G2, G6, G8, G10, statistical sensitivity numerical values, the results are shown in Table 6.

As shown in Fig. 8 and Table 6, it is obvious that at the Arctic government level, the current inconsistent standardization and language, limited information dissemination channels, poor communication at high latitudes, improper supervision system, rules and regulations, lack of safety management system and outdated data are important factors that cause the ship management company to fail to identify important hazards in the waters, and the government and regulatory authorities need to pay more attention to these aspects.

5.1.2. *Shipping company management sensitivity analysis*

Since both the ship management company and the technical operation management belong to the management, and the coupling between the factors is more complicated, they are combined into one level for sensitivity analysis, and the results are shown in Fig. 9.

As shown in Fig. 9 and Table 7, it is obvious that at the management level, the current unupdated chart data; insufficient supervision; improper route planning; improper labeling of the chart; outdated data; irregularities; ship SMS conflict; underestimate the risk are important factors that cause the bridge team did not get sufficient preparation for sailing, which need to be paid more attention.

5.1.3. *Unsafe incidents and behavior sensitivity analysis*

In the same way, the sensitivity analysis of unsafe behaviors results is shown in Fig. 10.

As shown in Fig. 10 and Table 8, it is obvious that at the unsafe incident behaviors level, the current inefficient use of navigation equipment; misjudgment; lack of navigation equipment; insufficient preparation for sailing; dependent equipment; improper operation; unupdated chart data are important factors that cause the crew did not find the shoal.

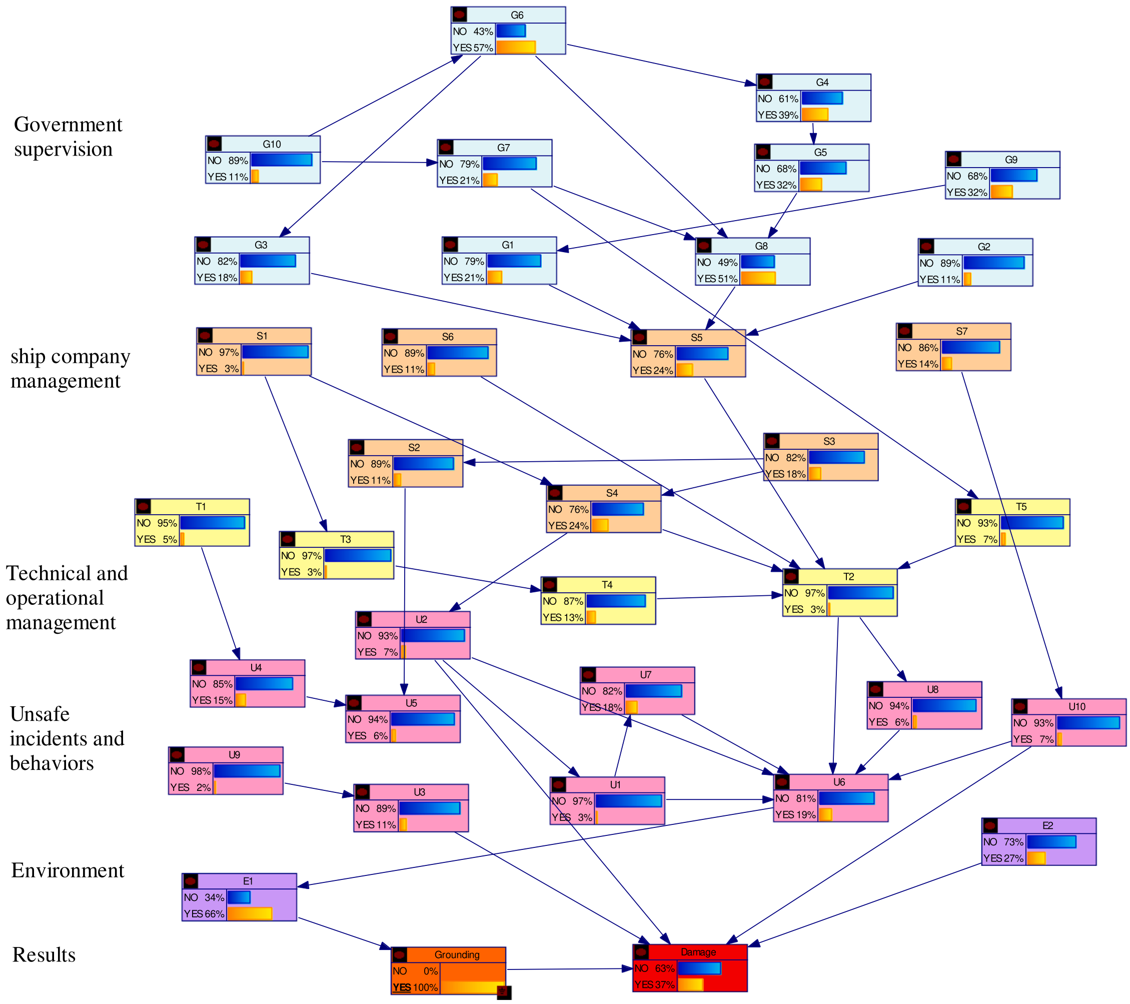


Fig. 5. Probability of further damage after a ship grounded under certain conditions in Arctic waters.

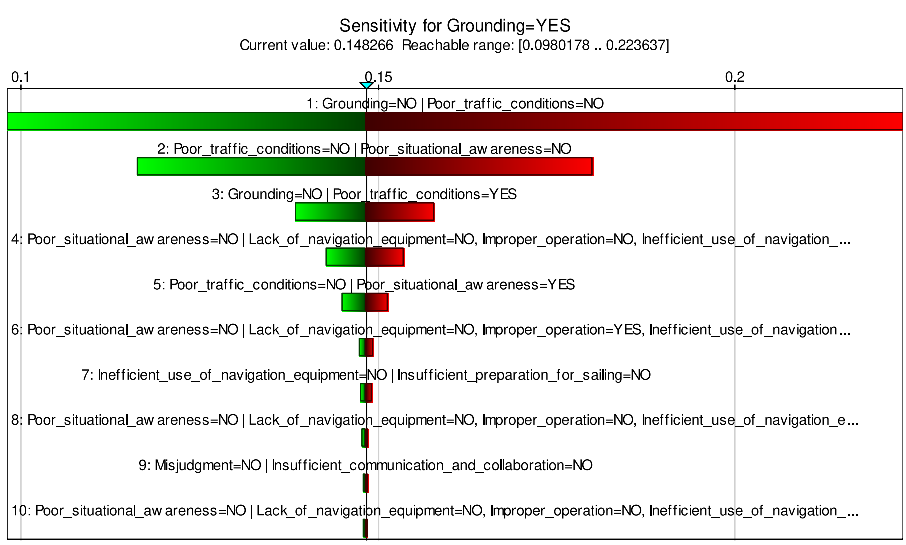


Fig. 6. Tornado diagram with “ship grounding” as the target variable for sensitivity analysis.

5.2. RCOs analysis

According to the above results of scenarios analysis, by learning lessons from the Clipper Adventurer grounding accident, laws, policies, and management mechanisms relating to ship safety management have been improved.

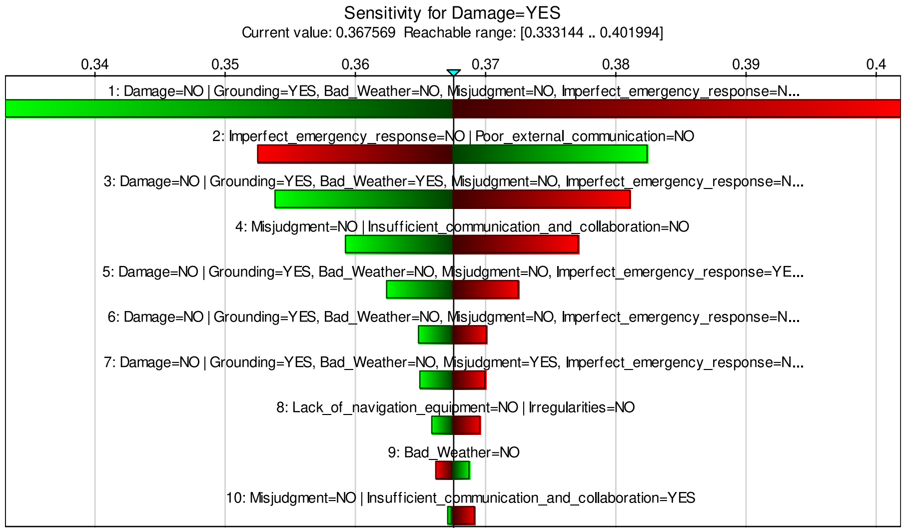


Fig. 7. Tornado diagram with "ship damaged" as the target variable for sensitivity analysis after the ship grounded.

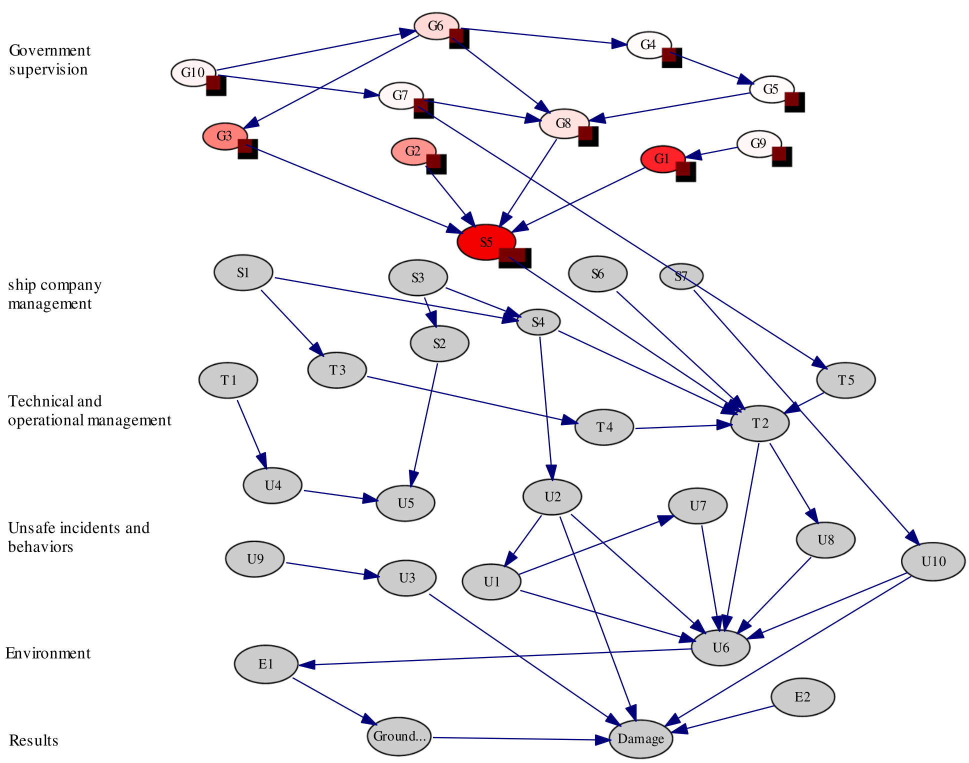


Fig. 8. Node influence degree under government supervision level in the BN model.

Table 6.
Maximum absolute sensitivity values for the variables and corresponding parameters in the BN model, when *"S5"* is set as the target (output) variable.

No	Variable	Variable name	Maximum sensitivity
1	G1	Inconsistent standardization and language	0.178
2	G3	Limited information dissemination channels	0.094
3	G2	Poor communication at high latitudes	0.077
4	G6	Improper supervision system, rules and regulations	0.022
5	G8	Lack of safety management system	0.017
6	G10	Outdated data	0.007

5.2.1. *Governments and associations in Arctic waters*

According to the discussion of the paper, inconsistent standardization and language, limited information dissemination channels, poor communication at high latitudes, and outdated data are important risk factors. The Arctic waters are linked to eight countries. Each country has its own standards for policies and regulations in its own waters, meaning ships face inconsistent standards when sailing in the Arctic. These eight countries should form a unified organization to manage Arctic waters, which would be responsible for navigation services in Arctic waters. These services could include, for example, navigation risk notification, surveying of unknown waters, updating charts of Arctic waters, infrastructure construction, rapid response rescue activities, and unification of communication standards.

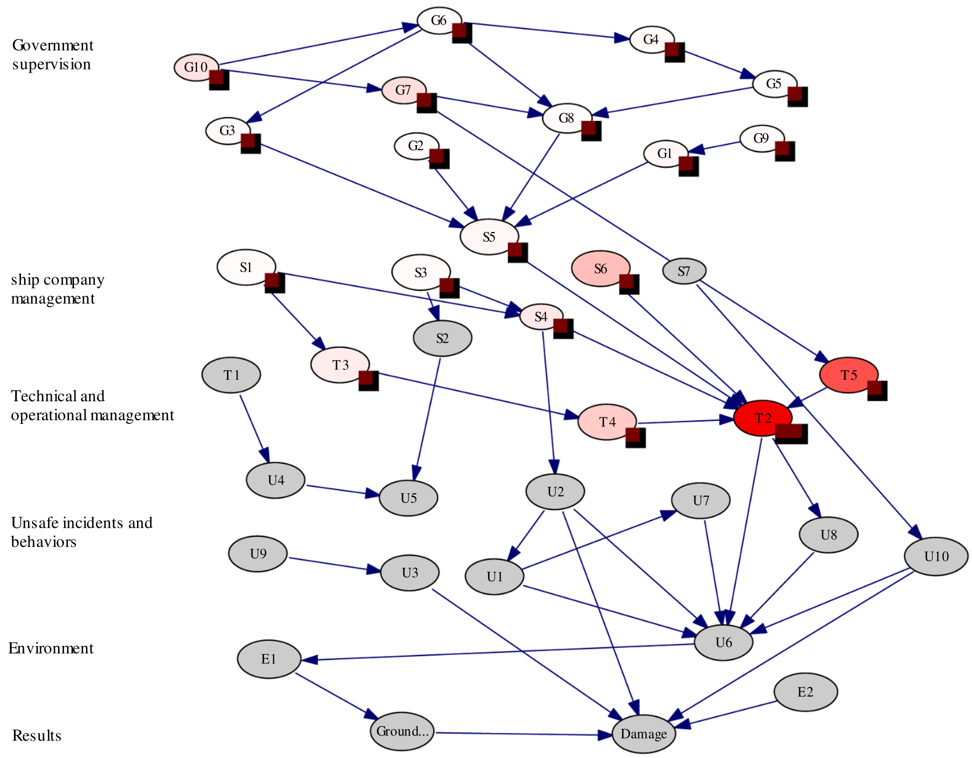


Fig. 9. Node influence degree under management level in Arctic waters.

Table 7.
Maximum absolute sensitivity values for the variables and corresponding parameters in the BN model, when *"T2"* is set as the target (output) variable.

Ranking	Variable	Variable name	Maximum sensitivity
1	T5	Unupdated chart data	0.188
2	S6	Insufficient supervision	0.059
3	T4	Improper route planning	0.047
4	G7	Improper labeling of the chart	0.026
5	G10	Outdated data	0.025
6	S4	Irregularities	0.018
7	T3	Ship SMS conflict	0.013
8	S5	Underestimate the risk	0.008

In addition, for risk factors such as improper supervision system, rules and regulations and lack of safety management system, as the number of ships navigating in polar waters continues to increase, the classification societies of various countries have issued relevant operating regulations for such ships. The IMO "Polar Rules" were formally put into effect on January 1, 2017. Moreover, several safety measures for polar sailing ships are included in the International Convention for Safety of Life at Sea (SOLAS) Convention, Annex Chapter XIV, which came into effect on January 1, 2017. The Polar Rules and other international rules effectively reduce the risks encountered by ships when navigating in special waters. The governments of all polar countries should abide by relevant navigation rules to improve the safety of Arctic ships.

5.2.2. Shipping company

Irregularities and underestimating the risk are important risk factors at the ship company management level. In 1993, IMO passed the ISM Code, stipulating that shipping companies and their ships should establish a scientific and systematic SMS, which would improve the safety management system of the company and its ships, as well as crew working practices, to reduce the well-known risks associated with Arctic operations. It is also necessary to ensure the availability and completeness of equipment during the voyage and reduce the risk of lack of navigation equipment and insufficient preparation for sailing. In addition, the education and training of the crew are very important, and shipping companies should improve the overall quality of crews and their knowledge of sailing in Arctic waters.

Insufficient supervision is also an important factor leading to accidents at the shipping company management level. Zhang et al. [33] pointed out that when ships sail in Arctic waters, shipping companies need to pay attention to external factors and unsafe regulations. Ship navigation standards and rules in arctic ice cap waters should be strictly followed to improve ship operation. At present, many shipping companies have opened up Arctic routes. Due to the special geographical environment of the Arctic, these shipping companies need to strengthen their internal management and conduct timely audits to ensure the safe and effective operation of this SMS and reduce the conflict of ship SMS. Based on IMO Resolution A893(21) [84] and SOLAS, the International Chamber of Shipping (ICS) produced the Bridge Procedures Guide. This guide makes it clear that the bridge team should complete a route plan assessment before voyage planning, including local area warnings. However, in the final voyage plan of the Clipper Adventurer, the ship management company did not strictly follow the guidelines to review the plan, and information on key risk factors was still missing, which, in turn, led to the grounding accident. Arctic shipping companies must strictly abide by the relevant policies and facilities, and strengthen internal audits to verify the effectiveness of policy implementation, thereby reducing risk factors and improving risk management.

5.2.3. Crew and passengers

The people aboard the ship can be divided into crew and passengers. In the crew, the factors that affect the safety of navigation are mainly physiological, psychological, skill-based, and attitudinal. Through discussion and analysis, it is concluded that inefficient use of navigation equipment, misjudgment, lack of navigation equipment, insufficient preparation for sailing, dependent equipment and improper operation are important risk factors for human level. Therefore, appropriate measures should be taken to ensure good working conditions for the

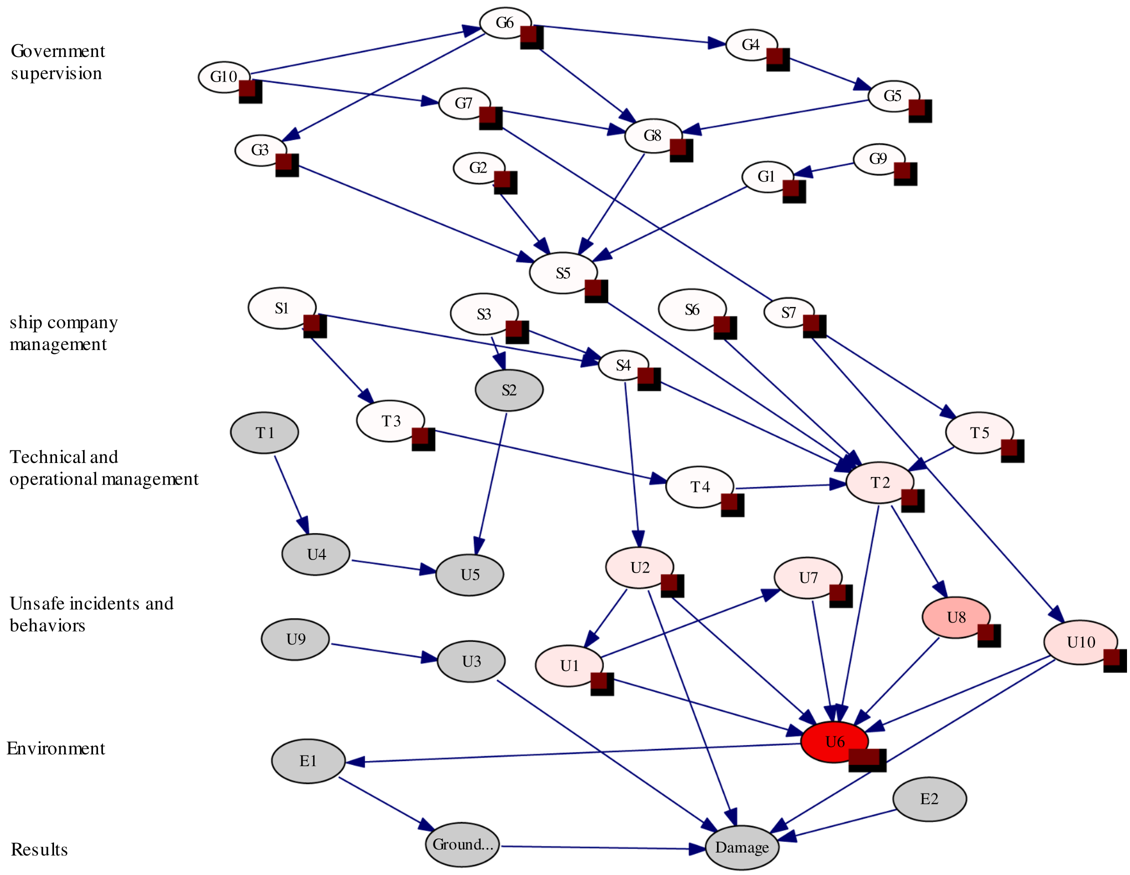


Fig. 10. Node influence degree under unsafe incidents and behavior level in Arctic waters.

Table 8.
Maximum absolute sensitivity values for the variables and corresponding parameters in the BN model, when *"U6"* is set as the target (output) variable.

No	Variable	Variable name	Maximum sensitivity
1	U8	Inefficient use of navigation equipment	0.113
2	U10	Misjudgment	0.042
3	U2	Lack of navigation equipment	0.032
4	T2	Insufficient preparation for sailing	0.031
5	U1	Dependent equipment	0.031
6	U7	Improper operation	0.027
7	T5	Unupdated chart data	0.014

crew, in terms of meeting their psychological needs. This might constitute practices such as implementing reasonable work and rest times and creating a good working environment. In the field of skills, it is also necessary to ensure that the crew use equipment reasonably, can work efficiently and with high quality and can strictly abide by the navigation rules [26]. In terms of psychological counseling of the crew, certain measures might be adopted, such as improving navigational mental health education. It would be beneficial to review the training of crew members and improve their safety awareness.

Passengers are often the most vulnerable to danger in grounding accidents, especially in cold Arctic waters. Passengers should therefore be granted the facility of improving their safety awareness and mastering the operation of rescue equipment on ships, and have certain self-escape capabilities, especially during ice navigation.

6. Conclusion

This paper has proposed a framework for the causation analysis of grounding accidents in Arctic shipping based on AcciMap and BN. Taking the grounding accident of the Clipper Adventurer in Arctic waters as an example, a case study of grounding accident causes and scenario evolution in Arctic waters has been discussed. The AcciMap model can simulate a complex social and technological environment. The unfolding of an accident is shown in diagram form to illustrate the interrelationships of accident causes. Under the model established by AcciMap, BN can use objective data to reason about accident evolution and perform quantitative calculations for the purpose of studying accidents to provide a holistic perspective. Under the framework provided by AcciMap, important nodes are identified and analyzed through BN. The Clipper Adventurer accident resulted from the combined effects of five levels of risk factor: government supervision, the ship management company, technical and operational management, unsafe incidents and behavior, and environmental conditions. A total of 34 risk factors across all five levels triggered the Clipper Adventurer grounding accident.

The results show that the poor traffic conditions, poor situational awareness, and inefficient use of navigation equipment are important factors in grounding accidents, and under the environmental conditions and ship conditions shown in Fig. 5, the probability of further damage to the ship is 37% when the ship is grounding. Among them, BN has determined important factors at all levels through scenario analysis. Inconsistent standardization and language, limited information dissemination channels, and poor communication at high latitudes are important factors at the government level; updated chart data; insufficient supervision, improper route planning are important factors at the management level; inefficient use of navigation equipment, misjudgment, lack of navigation equipment are important factors in unsafe incident behaviors level. Based on this, relevant governments, organizations, institutions, and shipping companies will be able to identify risk factors based on past accidents in response to the inherent problem of grounding accidents in Arctic waters, thereby eliminating potential safety hazards. At the government level, Arctic countries should formulate unified organizations and relevant polar rules to ensure safe navigation in Arctic waters. Shipping companies must establish effective safety management systems and comply with relevant policies and regulations in order to strengthen internal audits and substantially reduce accidents. In terms of personnel, the training of seafarers and the self-rescue ability of passengers should be enhanced to realize a systematic improvement in Arctic navigation risk management.

CRediT authorship contribution statement

Shanshan Fu: Writing – original draft, Writing – review & editing, Validation, Methodology, Funding acquisition, Data curation, Conceptualization. **Yuerong Yu:** Writing – original draft, Writing – review & editing, Software, Data curation, Conceptualization. **Jihong Chen:** Writing – review & editing, Funding acquisition. **Yongtao Xi:** Writing – review & editing. **Mingyang Zhang:** Writing – review & editing, Validation.

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 manuscript entitled "A Framework for Quantitative Analysis of the Causation of Grounding Accidents in Arctic Shipping".

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2022.108706.

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