Chapter 9

Navigational risk factor analysis of Arctic shipping in ice-covered waters

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1 Introduction

Recently, with global warming and a large amount of sea ice melting, the Arctic sea ice has started to decline in volume, extent, and thickness, and the extremely valuable Northern Sea Route (NSR) has led to an increased interest in Arctic shipping activities, as this is the shortest track between northern Europe and northeast Asia (Beveridge et al., 2016; Fu et al., 2017; Zhang et al., 2018; Schøyen and Bråthen, 2011; Zhang et al., 2017a,b,c). The latter is the reason why many shipping companies aim to use this sea route to decrease trip times and costs (Fu et al., 2016; Zhang et al., 2016, 2017a,b,c, 2018). Moreover, hydrocarbon resources in Arctic areas can be exploited and transported during such trips.

Merchant ships typically navigate Arctic waters for approximately four to five months, depending on ice conditions. It is very difficult to ensure the safety of navigation in Arctic ice-covered waters when vessels sail independently and face harsh conditions, such as the presence of sea ice, low temperatures, electromagnetic interference, and other complex environmental conditions (Stoddard et al., 2015; Goerlandt et al., 2016; Fu et al., 2017; Khan et al., 2018; Ostreng et al., 2013; Zhang et al., 2018). At the same time, ordinary vessels lack icebreaking capability, meaning that they cannot ensure ship safety when sailing independently in a harsh ice environment; this can, in turn, easily lead to ice accidents (Kum and Sahin, 2015; Zhang et al., 2017a,b,c; Fu et al., 2016).

In order to expand the navigational window, many ships are escorted or convoyed by an icebreaker. Thus, two shipping mode scenarios in Arctic ice-covered waters can be conceptualized: *independent navigation and navigation*

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with icebreaker assistance. The latter can be seen as organized into four identified icebreaker operations: *escort, convoy, breaking a ship loose,* and *towing* (Goerlandt et al., 2017; Valdez Banda et al., 2015). Despite these measures, Arctic ice-covered waters continue to be regarded as harsh environments for shipping. There is an overall high degree of uncertainty about this navigational environment and ship safety management within it. As an example, accident statistics in ice-covered waters in the Russian sea area (Goncharov et al., 2011; Lobanov, 2013), and in the gulf of the Finnish sea area (Valdez Banda, 2017), are presented in Fig. 1.

There are two types of ship accidents, from which three typical accident scenarios in Arctic ice-covered waters can be derived. As can be seen from Fig. 1, in the Finnish sea area 22% of all accidents are collisions. That percentage increases to 48% for an ice-ship collision (most hull damage is caused by ice-ship

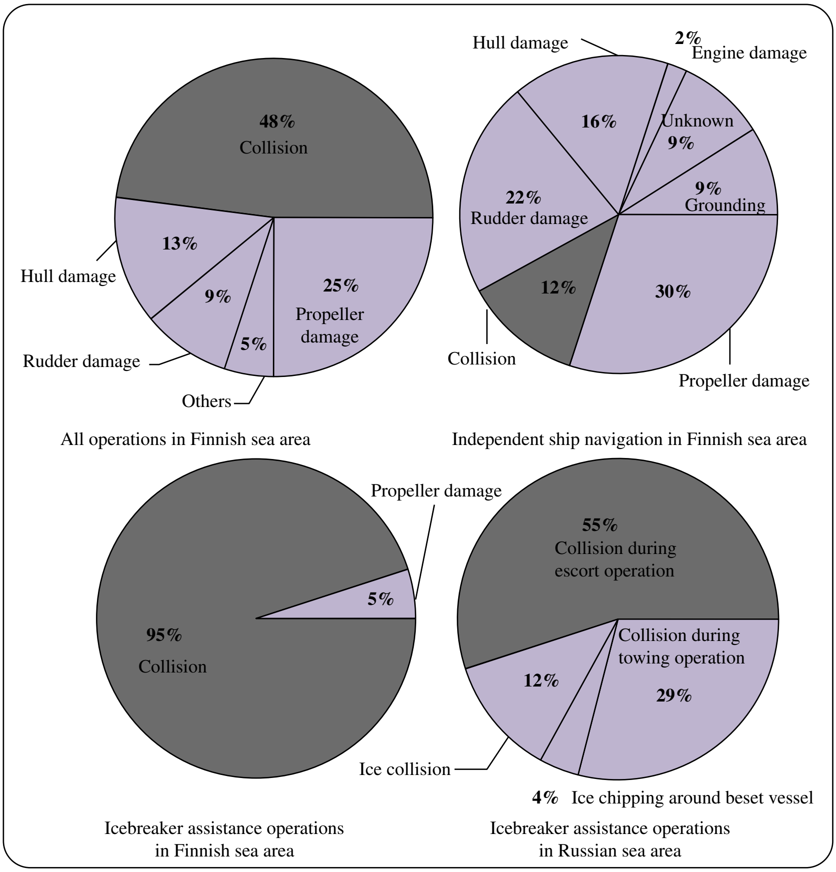

FIG. 1 Accident statistics for ice-covered waters in the Russian Sea and Finnish Sea areas (Valdez Banda, 2017; Zhang et al., 2018).

collisions, and most propeller and rudder damage by ice-ship collisions during backing operations when ships get stuck in ice), and the percentage of grounding on ice is 9% out of all accidents when ships are independently navigated. In the icebreaker assistance scenario, i.e., in the Finnish sea area, it can be seen that 48% of all accidents are collisions, and 95% of all accidents occur under icebreaker assistance. In the Russian sea area, collisions during the escort operation can be seen to account for 55% under similar assistance conditions. Despite different ways of statistics in the Finnish and Russian sea areas, the statistics indicate that ship collisions (ice-ship collision and ship-ship collision) constitute the most typical accident type in ice-covered waters, in turn implying that collision accidents should be avoided in ice-covered waters.

In Arctic ice-covered waters, it is difficult to ensure navigational safety when ships sail independently and face harsh conditions (Stoddard et al., 2015; Goerlandt et al., 2016; Fu et al., 2017; Khan et al., 2018; Ostreng et al., 2013). At the same time, ordinary vessels lack ice-breaking capability, making them unable to sail independently in a harsh ice environment, which can easily lead to becoming stuck in ice (Kum and Sahin, 2015; Zhang et al., 2017a,b,c; Fu et al., 2016). Ship accidents frequently result in propeller or rudder damage. Meanwhile, ships navigating with an icebreaker reduce the risk of ice-ship collisions, becoming stuck in ice, and grounding on ice. Nevertheless, collision accidents also occur between icebreakers and assisted ships. Therefore, navigational risk factors should be analyzed in order to improve the safety level of ice navigation.

Above all, the navigational risks of ice-going ships cannot be ignored in Arctic ice-covered waters. The literature contains some studies that have been carried out with a focus on independent ship navigation in ice-covered waters. The risks of ship collision and grounding have been analyzed using a root cause analysis method in Arctic ice-covered waters (Kum and Sahin, 2015). Another study analyzed an Arctic shipping accident scenario in order to identify essential accident risk factors in a potential accident scenario (Afenyo et al., 2017). Risk analysis models of ships stuck in ice have also been proposed (Fu et al., 2015, 2016; Montewka et al., 2015). Another line of work has focused on the application of risk-based design principles to Arctic shipping (Bergström et al., 2016; Ehlers et al., 2017). Other studies have been conducted with a focus on icebreaker ships in ice-covered waters. The navigational risks of collision under icebreaker assistance have been found to be different from other ship collision accidents, estimated to be higher in ice-covered waters than in open waters (Zhang et al., 2014; Franck and Holm Roos, 2013; Sulistiyono et al., 2015).

Accordingly, navigational risk factors should be investigated under extreme conditions. Furthermore, the analysis of the risks of navigational operations in ice-covered waters suggests that escort and convoy operations under icebreaker assistance are quite dangerous when performed in ice-covered waters. Overall, whether navigating independently or under icebreaker assistance, ship accidents present the most significant risk in Arctic ice-covered waters (Valdez Banda et al., 2016; Goerlandt et al., 2017; Zhang et al., 2018).

However, the existing studies are limited in terms of their risk analysis of typical operational conditions or accidents, such as collisions between ships, between a ship and ice, or grounding accidents.

In particular, a systematic and multifactorial analysis of navigational factors is presented in the chapter, which aims at identifying and classifying collision risk factors. The research relies on the HFACS and text mining approaches, which are utilized to identify and classify the collision risk factors mentioned in accident reports and research papers on ice-covered waters. A Fault Tree model is proposed, employing a cause-consequence analysis of navigational risk factors according to accident reports and expert knowledge. Following this, a qualitative analysis is carried out to analyze collision risk factors using structural importance degree coefficients and minimum cut sets, thus providing a theoretical basis for the formulation of risk control strategies.

The rest of this chapter is organized as follows: Section 2 describes the research methodology and materials regarding navigational risk factors in Arctic ice-covered waters. The model development and results, which identify navigational risk factors, are presented in Section 3. The navigational risk factors analysis is carried out in Section 4, and Section 5 presents the discussion and conclusions.

2 Method and data

In this chapter, in order to identify and classify the factors contributing to accidents, and according to the characteristics of three typical accidents in Arctic ice-covered waters, the appropriate methods and models are proposed based on the available data. According to accident statistics and the scientific literature, accidents caused by human and organizational factors (HOFs) account for 90% of the total number of maritime accidents (Chauvin et al., 2013). Thus, with a focus on ship collision under icebreaker assistance, the HFACS and fault tree models are used here to analyze contributory collision factors with reference to historical accident reports and expert knowledge. So with a focus on accident scenarios occurring during independent ship navigation, a text mining approach is used to identify the contributory accident factors based on scientific research papers, while the fault tree model is applied to analyze the risk factors. A flowchart of the navigational risk factor analysis of typical accident scenarios in Arctic waters is shown in Fig. 2.

2.1 The HFACS framework

The Human Factors Analysis and Classification System (HFACS) framework, initially proposed by Wiegmann and Shappell (2003), consists of four layers: *organizational factors*, *unsafe supervision*, *preconditions for unsafe acts*, and

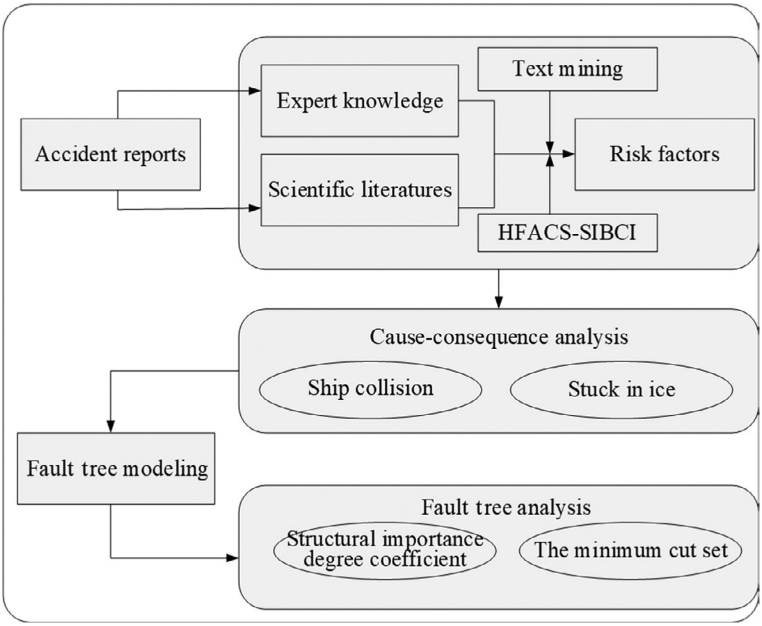

FIG. 2 Flowchart of navigational risk factor analysis of typical accident scenarios in Arctic ice-covered waters.

unsafe acts. Zhang et al. (2018) proposed a fifth layer by which to analyze the human and organizational factors involved in ship collisions under icebreaker assistance. This modified, five-layer HFACS framework was applied to the current study in order to classify and identify accident-contributing factors, with reference to accident and incident reports. In these applications of the HFACS framework to specific contexts, the contributing factors of each layer were interpreted in specific accident situations. Overall, the HFACS framework may be seen as a valid one for risk assessment and risk analysis, where the factors of each layer change continuously according to the research object. In addition, the HFACS-Ship-Icebreaker Collision in Ice-covered waters (HFACS-SIBCI) is utilized to identify and classify the collision risk factors during icebreaker assistance.

2.2 Fault tree analysis (FTA)

The FTA is a typical method and an accidental evolutionary logic analysis tool used to estimate the safety and reliability of a complex system. It has been used conclusively to establish the relationships among accident risk factors (Zhou et al., 2017; Kum and Sahin, 2015; Wang et al., 2013). Moreover, the FTA also has the capacity to reproduce the evolution of underlying factors and high-level accidents, thus aiding understanding of the development course of collision accidents.

In the FT model, following the identification and classification of collision risk factors, this chapter further explored the causes and consequences of accidents by analyzing the relationship between the latter and navigational risk factors, using the FTA. The collision accidents were also qualitatively analyzed based on the structural importance degree coefficient and the minimum cut sets. The essence of the FTA is to establish logical relationships among certain factors based on the mathematical logic theory. The logical relationships are denoted by OR and AND gates. The formulas are shown in Eqs. (1), (2)

$$\varphi(x) = \sum_{i=1}^{n} x_i = \{x_1 + x_2 + \cdots + x_n\} \tag{1}$$

$$\phi(x) = \coprod_{i=1}^{n} x_i = \{x_1 \times x_2 \times \cdots \times x_n\} \tag{2}$$

where $\varphi(x)$ and $\phi(x)$ denote the top event used to describe the complex system state, and $x_{i,}$ the basic factors of i. The output event $\varphi(x)$ presented by the OR gate occurs when at least one input factor occurs, and the output event $\phi(x)$ presented by the AND gate occurs when both input factors occur (Lee et al., 1985).

In the qualitative analysis, the probabilities of the occurrence of different navigational risk factors were assumed to be equal. At the same time, the institutional importance of all risk factors was calculated using the minimum cut sets of the proposed FT model. The structural importance degree of the FT was also calculated. The latter denotes the importance of each basic event based on the structure of the fault tree. For the purposes of the current chapter, the probabilities of all of the navigational risk factors of the three accident scenarios were assumed to be equal in qualitative analysis using FT. Then, the influence of the upper event on the top event was analyzed and the results sorted according to the structural importance degree. Finally, the risk control options (RCOs) were developed according to the structural importance degrees obtained through the qualitative analysis, using the proposed FT for ship collision accidents under icebreaker assistance in ice-covered waters.

Generally speaking, there are two ways to calculate the structural importance degree of the FT: (i) calculate the structural importance degree coefficient, and (ii) use the minimum cut sets for judgment, as now explained in further detail.

(a) Calculate the structural importance degree coefficient of each basic event.

Assume that the state is (0) when the system operates normally, and (1) when the system fails. Then, when the state of the basic event changes (usually from normal operation to failure), the system may experience the following four changes:

- The system changes from normal operation to failure $\{(0) \rightarrow (1)\}$.
- The system remains in a normal working condition $\{(0)\}$.
- The system remains in a state of failure $\{(1)\}$.
- The system changes from a state of failure to normal operation $\{(1) \rightarrow (0)\}$.

The structural importance degree coefficient can be obtained from Eq. (3):

$$I(i)=\begin{cases}\frac{1}{2^{n-1}}\sum\left[\varphi\left(1_i,x\right)-\varphi\left(0_i,x\right)\right]\text{OR gate,}\\ \frac{1}{2^{n-1}}\sum\left[\phi\left(1_i,x\right)-\phi\left(0_i,x\right)\right]\text{AND gate}\end{cases}\tag{3}$$

where $I(i)$ denotes the structural importance degree coefficient, $\varphi(x)$ and $\phi(x)$ represent the top event used to describe the complex system state, and x_i are the basic factors of i (Rausand, 2013).

(b) Determine the order of the degrees of structural importance by using the minimum cut sets.

2.3 Textual data mining approach

To construct ship accident scenarios in Arctic ice-covered waters using a text mining approach, the data first need to be categorized according to their type, and appropriate data mining tools need to be considered. In terms of the above analysis, the focus of this chapter lay in mining the scientific research papers found on the Web of Science, in particular. The most common text mining system is that of the Institute of Computing Technology, Chinese Lexical Analysis System, which can segment and count Chinese text data. However, this system has obvious merit in that it cannot conclusively identify the terminologies in one specific field. Compared with this system, the R language is an open software platform, which can be added according to the user's needs in order to undertake functions such as statistical analysis, analytical processing, and visualized results. As a result, the analysis and extraction of navigational risk factors in the current chapter were realized by utilizing the R language and related software package to extract and analyze the scientific literature regarding independent navigation in Arctic ice-covered waters.

2.4 Accident reports and scientific literature

In order to analyze navigational risk factors, official accident reports and scientific literature pertaining to accident analysis were used in this research. Official accident reports play an essential role in risk factor analysis because they present valuable and detailed information of said accidents that is compiled by an accident investigation board (Mazaheri et al., 2015). Examples of the latter include the Swedish Accident Investigation Board and the Marine Accident Investigation Branch (MAIB) from the United Kingdom, and the Russian FleetMon and Arctic database. Specifically, 17 accidents that had occurred during 1989–2017—and information about which was freely accessible to the public—were considered for the current study and analyzed so as to uncover the collision risk factors under icebreaker assistance. The collision risk factors mentioned in the accident reports are considered and further classified based on the proposed model. For their part, ship accident reports and the scientific literature were analyzed using a text mining approach to identify and classify the navigational risk factors in the context of ships making independent voyages in Arctic ice-covered waters, such as Web of Science, Scopus, and conference proceedings.

3 Model and results

In order to analyze the navigational risk factors, the analysis procedure was divided into three stages: (1) The navigational risk factors were identified using the HFACS-SIBI model (Zhang et al., 2018), based on official accident reports and experts' knowledge, with the focus on collision accidents occurring in the context of icebreaker assistance. (2) The navigational risk factors were identified using the text mining approach based on scientific papers and experts' knowledge, with the focus on ships being stuck in ice and collisions with ice during independent ship navigation. (3) The fault tree was used to establish the fault model for accident risk analysis in Arctic ice-covered waters; the model's development and results are described in the following section.

3.1 Ship collision factors analysis under icebreaker assistance

3.1.1 HFACS-SICI

The HFACS-based ship collision risk analysis model of the HFACS-SIBCI (HFACS-Ship-Icebreaker Collision in Ice-covered waters) was applied in this study to classify and identify ship collision factors, which consisted of five risk factor analysis levels and 28 classification categories, as shown in Fig. 3.

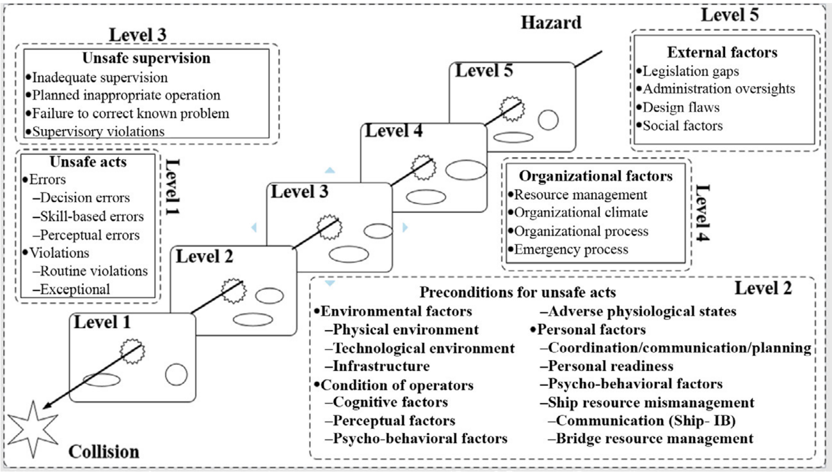

FIG. 3 Accident risk factors classification model based on HFACS-SIBCI.

The HFACS-SIBCI was thus established as a five-level framework (Zhang et al., 2018). In particular, the 28 classification categories contain fundamental collision risk factors affecting collision accidents in the context of icebreaker assistance.

The contributing factors mentioned in the accident reports were identified as risk factors. To begin with, ship collision risk factors under icebreaker assistance were identified using the five-layer HFACS-SIBCI model. The classification model was then utilized to classify ship collision factors based on the categories containing the five collision risk analysis levels and 28 classification categories, such as *decision errors*, *technical errors*, and *legislation gaps*. The HFACS-SIBCI accident risk factors classification model is shown in Fig. 3, which also describes the classification categories in detail (Zhang et al., 2019).

3.1.2 Ship to icebreaker collision risk factors identification

For the purposes of the current chapter, ship collision accidents were classified as occurring between icebreakers and assisted ships, and a hierarchical structure of ship collision risk factors was established. The collision risk classification procedure was as follows: First, ship collision-contributing factors that were mentioned in the accident reports were selected. Second, additional ship collision factors were identified by experts in the field, such as *wrong icebreaker course* and *engine failure*. The latter step was employed so as to ensure that key collision factors were not missed in the case of a lack of accessible accident reports. At the same time, the relevant literature was referenced in order to verify the results regarding ship collisions in open water (Chauvin et al., 2013) and Arctic ice-covered waters (Kum and Sahin, 2015), as shown in Zhang et al. (2018). The ship collision factors in the context of icebreaker assistance were classified as shown in Table 1.

3.2 Analysis of ice-ship collision factors in the context of independent navigation

3.2.1 Text mining to identify risk factors

The text mining approach was used to analyze the scientific literature and identify the navigational risk factors during independent ship navigation. As previously stated, the R language platform was used to extract and analyze the relevant literature. The text mining approach was used to analyze the scientific literature from 2000 to 2018 in international journals indexed on the Web of Science platform. The visualization of the relationships between the authors of the papers found is shown in Fig. 4, and the visualization of major keywords in this research field is shown in Fig. 5.

3.2.2 Identifying ice-ship collision risk factors

68 papers were collected from Web of Science to undertake the risk analysis for ships in ice-covered waters. 51 of these published papers pertained to

TABLE 1 Navigational risk factors during icebreaker assistance.

No.	Risk factors		No.	Risk factors	
1	Unsafe acts	Maneuver failures of the assisted ship [L1]	13	Preconditions for unsafe acts	Communication equipment failure [L13]
2		Maneuver failures of the icebreaker [L2]	14		Poor communication between ships [L14]
3		Lack of situational awareness [L3]	15		Improper route selection [L15]
4		Negligence [L4]	16	Unsafe supervision	Wrong icebreaker course [L16]
5		Judgment failures [L5]	17		Exceeding safe speed limit [L17]
6	Preconditions for unsafe acts	Ice conditions [L6]	18		Unmaintained safety distance [L18]
7		Ice ridge [L7]	19		Deviation from suggested route [L19]
8		Poor visibility [L8]	20	Org. factors	Lack of emergency operation [L20]
9		Snow or rain [L9]			
10		Engine failure [L10]	21	External factors	Lack of icebreaking ability [L21]
11		Steering gear failure [L11]	22		Lack of engine power [L22]
12		Anticollision system failure [L12]	23		Anticollision rule gap [L23]

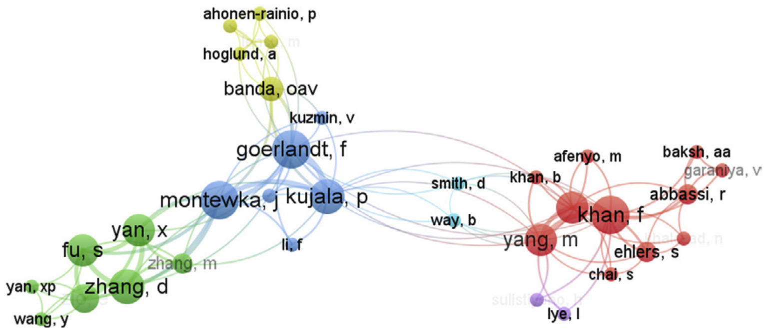

FIG. 4 Visualization of relationships between authors.

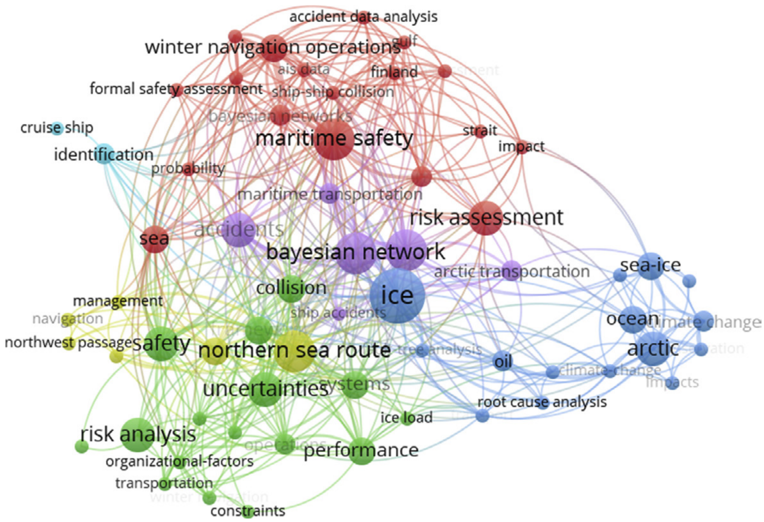

FIG. 5 Visualization of major keywords in the research field.

independent ship navigation, focusing on indication analyses of ships stuck in ice and ice-ship collision accident analyses. The scientific literature was analyzed using the proposed approach, as presented in Section 2.3. The collision risk identification procedure was as follows: First, the scientific literature was collected from Web of Science. This involved a preliminary selection of ship accident risk factors mentioned in the scientific literature as the word dictionary. Second, ship accident-contributing factors were selected using the text mining approach, based on the word dictionary. Finally, the relevant literature was referenced in order to verify the results, with the focus on ship accidents during independent navigation in ice. The navigational risk factors found in this context are shown in Fig. 6 and Table 2.

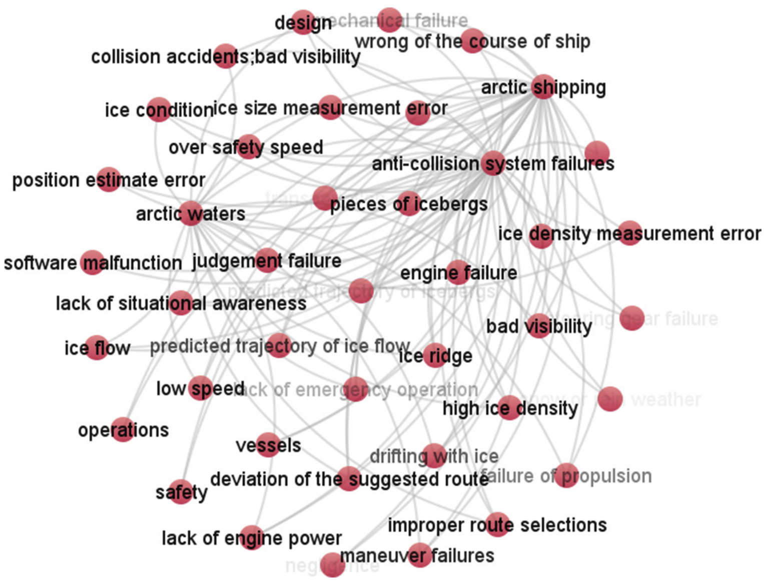

FIG. 6 Network view of navigational risk factors for ships navigating independently in ice.

TABLE 2 Navigational risk factors during independent ship navigation.

No.	Risk factors	No.	Risk factors
1	Drifting with ice [C1]	17	Snow or rain weather [C17]
2	Ice size measurement error [C2]	18	Steering gear failure [C18]
3	Pieces of icebergs [C3]	19	Wrong course [C19]
4	Predicted trajectory of icebergs [C4]	20	Engine failure [C20]
5	High ice density [C5]	21	Ice ridge [C21]
6	Ice density measurement error [C6]	22	Lack of engine power [C22]
7	Low speed [C7]	23	Lack of icebreaking ability [C23]
8	Predicted trajectory of ice flow [C8]	24	Improper route selections [C24]
9	Ice flow [C9]	25	Failure of propulsion [C25]
10	Bad visibility [C10]	26	Maneuver failures [C26]
11	Deviation from suggested route [C11]	27	Position estimate error [C27]
12	Ice conditions [C12]	28	Strong winds [C28]
13	Judgment failures [C13]	29	Software malfunction [C29]
14	Lack of emergency operation [C14]	30	Mechanical failure [C30]
15	Lack of situational awareness [C15]	31	Anticollision system failure [C31]
16	Negligence [C16]	32	Over safety speed [C32]

4 Navigational risk factors analysis using fault tree model

According to the statistics of accidents in Arctic ice-covered waters, shipping accidents constitute the most typical accident scenarios. Thus, this chapter focuses on the following three typical accident scenarios in Arctic ice-covered waters: a ship-icebreaker collision, a ship being stuck in ice, and an ice-ship collision. In order to establish the FT model for navigational risk analysis in ice-covered waters, the proposed statistical analysis procedure was carried out to analyze accident procedures (Zhang et al., 2018). In order to analyze the collision accident procedure, the Cause-Consequence Analysis approach was employed in order to draw the accident procedure map (Chen et al., 2013), an example of which is presented as follows: On 20th January 2011, at 0057 LT, a collision occurred between an icebreaker and an assisted ship during an icebreaker assistance operation at 65°05.1’5N, 026°41.0’1E. This ship collision accident was analyzed based on the HFACS-SIBCI model, in line with the Cause-Consequence Analysis approach shown in Fig. 7.

After identifying the navigational risk factors from the accident reports, the scientific literature, and experts’ knowledge, the navigational factors could be operationalized using the proposed model, which is a basis for the FT of collision accidents.

Many navigational risk factors can lead to an accident in Arctic waters, as argued in Sections 3.1.2 and 3.2.2. Lower events connect navigational risk factors.

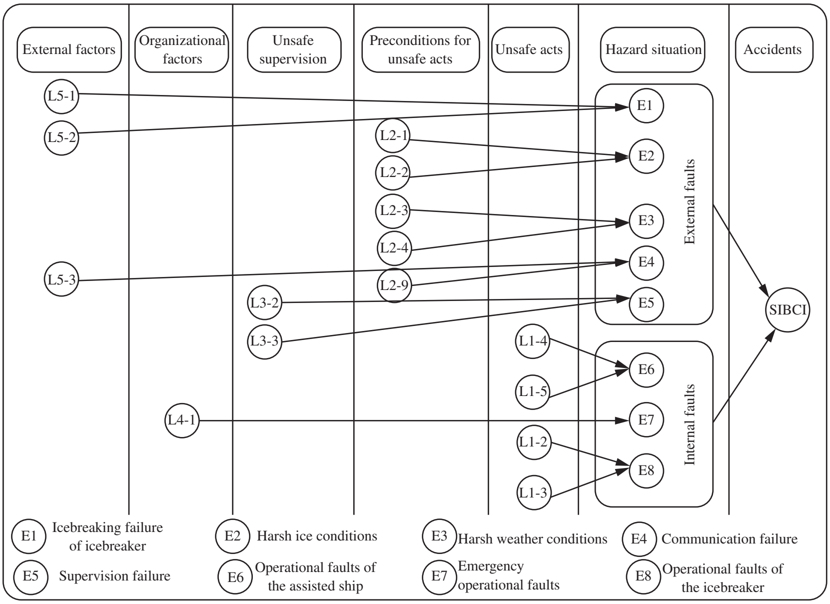

FIG. 7 Cause-consequence analysis with HFACS-SIBCI.

Thus, all branches can be terminated with the risk factors and intermediate factors using the FT model. Following this, this study analyzed the causes and consequences among the navigational risk factors. At the same time, hazard situations and events were defined as intermediate according to the causes and consequences analysis, as shown in Fig. 7. Accordingly, the preliminary FT was established using the causes and consequences analysis based on the accident reports. Finally, the FT model was established according to the hierarchical structure model based on the causes and consequences analysis, as detailed in the following section.

4.1 FT modeling for ship collision accidents under icebreaker assistance

For the purposes of this chapter, *ship collision risk under icebreaker assistance* was selected as the top event. Next, a ship collision risk analysis in the context of icebreaker assistance, due to both external and internal failures, was considered, according to the icebreaker assistance operation mode deemed suitable for the procedure of ship collision accidents. On one hand, icebreaker assistance is a complex navigation system involving the external environment, ships (the assisted ships and the icebreaker), crews, and coordination. This chapter analyzed *external operation errors* and *unsafe management* in line with the statistical HFACS-SIBCI analysis described in Section 3.1.1, and then established the FT of the external failure of icebreaker assistance operations, as shown in Fig. 8. Here, M5 denotes the failure of the icebreaker, M6 represents harsh navigational conditions, M6 contains two aspects (harsh ice conditions and harsh weather conditions), M7 denotes communication failure, and M15 supervision failure. In addition, the collision factors were connected by lower events; the relationships between the factors and events are shown in Fig. 7.

On the other hand, the specifics of icebreaker assistance imply its operation forms different from those of ships in open waters, in that tacit cooperation between the icebreaker and the assisted ship is required. Failures not only test the crews' skills but also require a high level of navigational performance under extreme conditions in ice-covered waters. At the same time, a detailed emergency operation plan needs to be developed.

Furthermore, icebreaker assistance involves many internal failures, in the sense that human errors can easily cause accidents. Accordingly, the FT of the internal failure of icebreaker assistance was established based on *internal operational faults* and *technical operational faults*, according to the Cause-Consequence analysis, as shown in Fig. 8. Here, M10 represents the operation faults of the assisted ship, M11 denotes emergency operation faults, and M12 stands for the icebreaker's operational faults. The FT model contains 23 risk factors influencing collision accidents under icebreaker assistance.

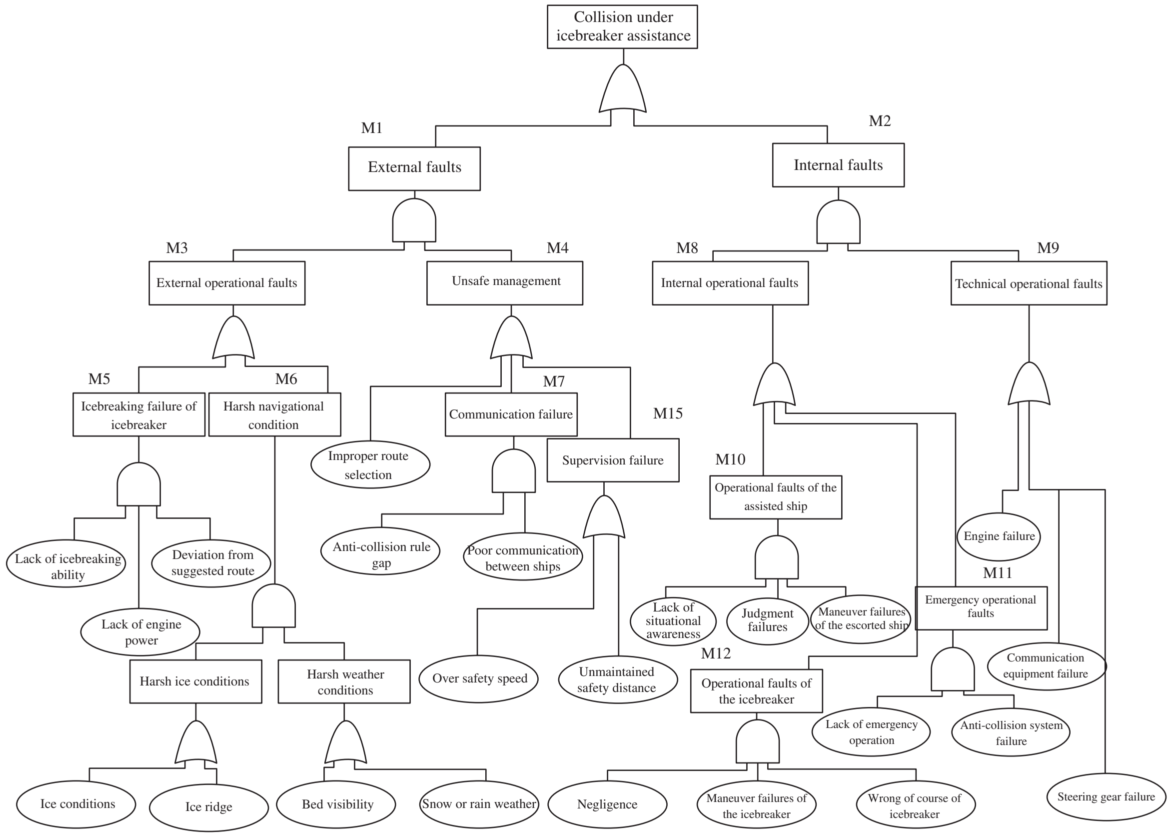

FIG. 8 Ship collision risk FT under icebreaker assistance.

4.2 FT modeling for ice-ship collision in the context of independent navigation

According to the results of the text mining of the scientific literature, the navigational risk factors during independent ship navigation in Arctic ice-covered waters were collected. The FTs of *stuck in ice* and *ice collision* were established based on accident procedure and experts' knowledge.

- FT of *ice-collision*—ice-ship accident

In this study, the FT modeling of ice-ship collisions in Arctic ice-covered waters selected *ice-ship collision* as the top event. Then, an ice-ship collision risk analysis during independent ship navigation was undertaken, taking into account navigational failures, unsafe management, and operational failures. The latter were considered according to the accident scenario of independent ice-going ships, based on the procedure of ice-ship collision accidents. The latter FT model is shown in Fig. 9.

- FT of *stuck in ice* of ice-ship accidents

To operationalize the FT modeling of ships stuck in ice in Arctic ice-covered waters, *ship stuck in ice* was chosen as the top event. Then, the risk analysis of ships being stuck in ice during independent ship navigation was conducted, considering navigational failures, unsafe management, and operational failures, based on the scenario of such independent ice-going ships undergoing the procedure consequent to being stuck in ice. The latter FT is shown in Fig. 10, highlighting 26 risk factors influencing the accident of ships being stuck in ice during independent ship navigation.

4.3 Qualitative analysis of collision risk

Based on the FT model proposed in Section 4.2, the qualitative analysis of navigational risk factors was carried out in light of the qualitative analysis of the FT. First, the minimum cut sets of the FT were determined. Next, the structural importance degree coefficients based on the minimum cut sets were calculated and sorted according to their sizes. Finally, the relationship analysis of different accident scenarios is conducted.

(1) Minimum cut sets of the proposed FT model

The cut set in a fault tree is a set of basic events whose (simultaneous) occurrence ensures that the TOP event occurs, where a cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set. According to the logical relationships among the various factors of the FT for ship collisions under icebreaker assistance, in this study the minimum cut sets were obtained using the Boolean algebra method (Gupta and Agarwal, 1983) (V2.19) (Easy Draw, 2013). The results containing minimum cut sets for different accident scenarios in Arctic ice-covered waters are shown in Appendix.

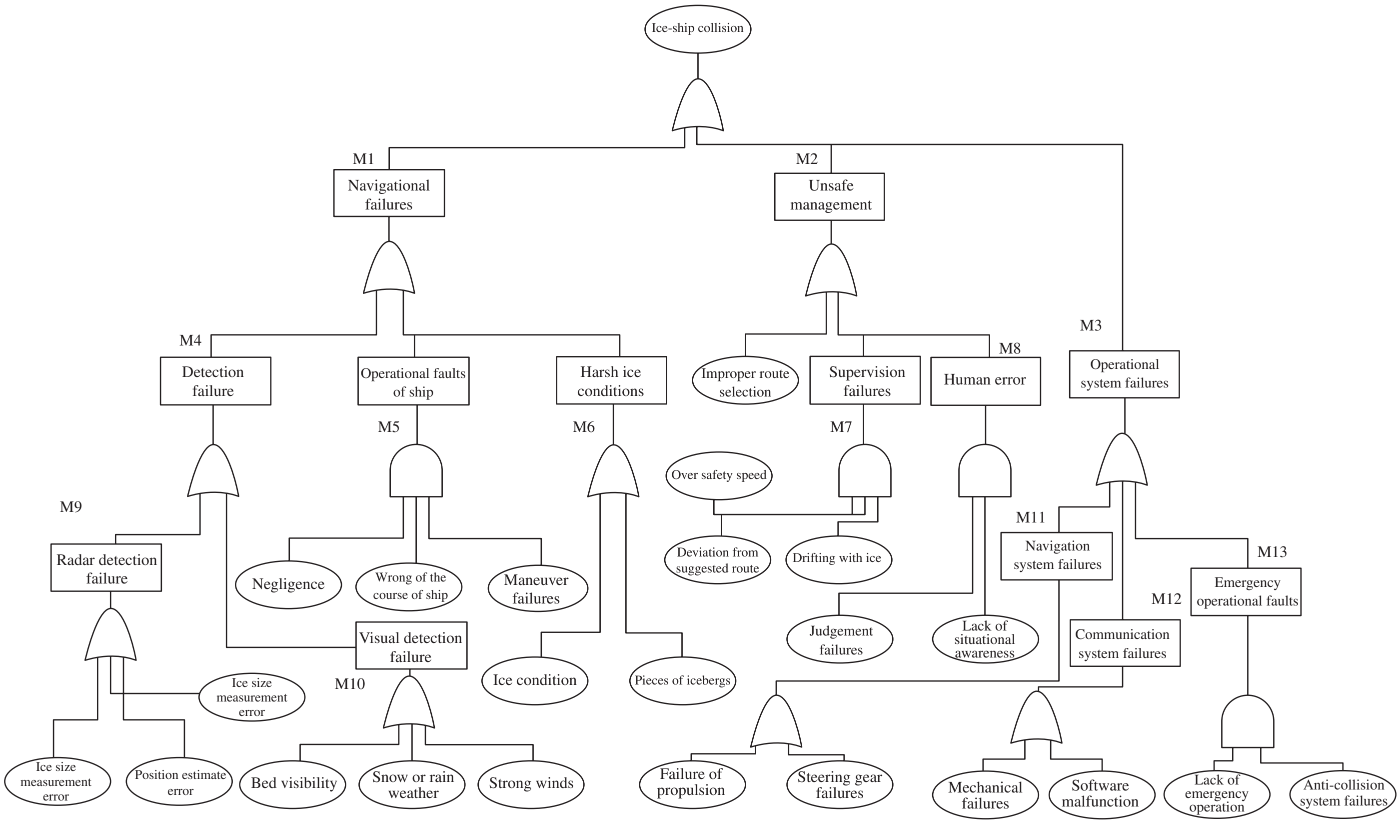

FIG. 9 Ice-collision risk FT during independent ship navigation.

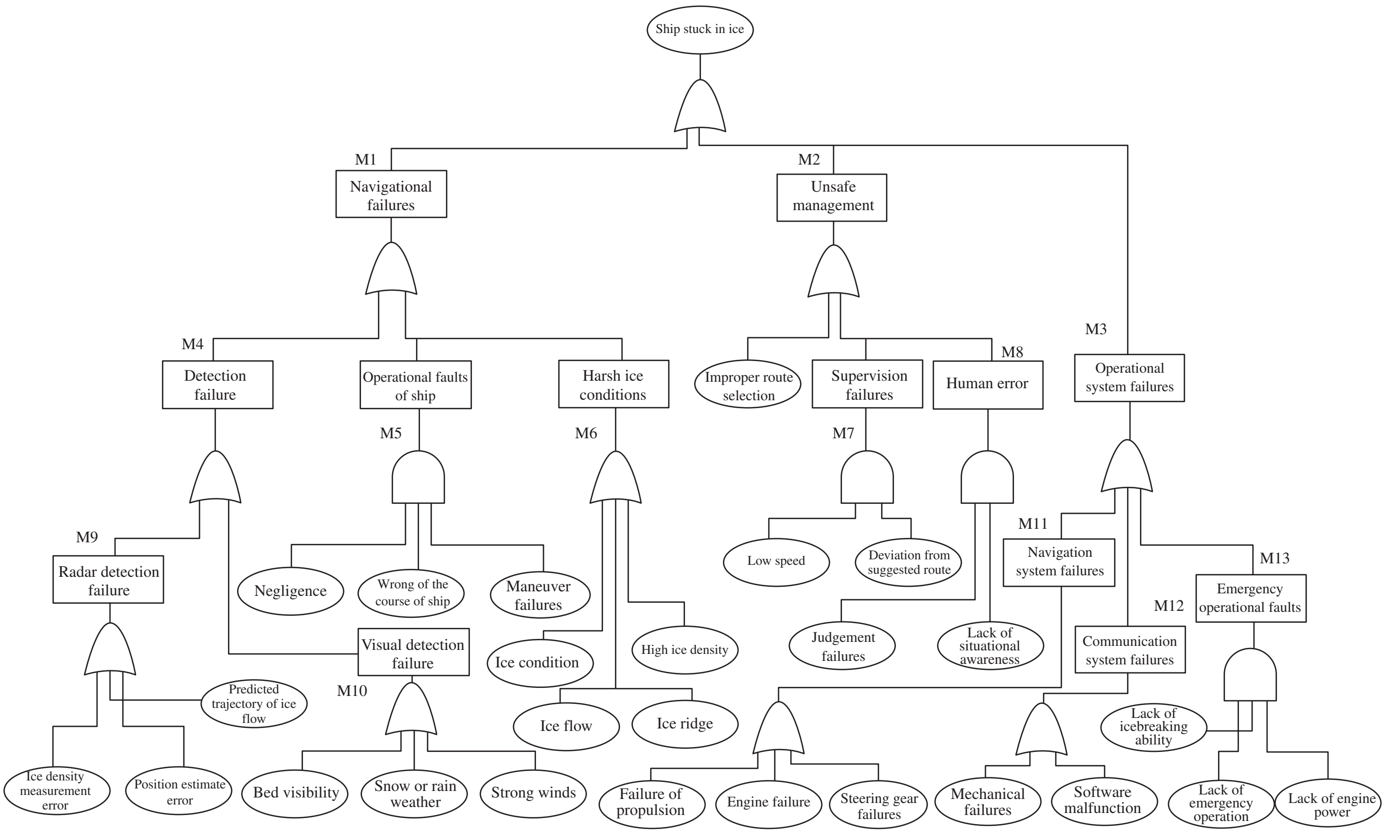

FIG. 10 FT of risk of ship being stuck in ice during independent ship navigation.

The minimum cut sets were obtained based on the dual law of Boolean algebra, which is a reflection of the system safety of navigation in ice. When there is no navigational risk factor in a minimum cut set, the accident does not occur as the top event. Therefore, by obtaining the minimum cut sets, it can be seen which basic events require RCOs in order to avoid collision accidents.

(2) The structural importance degree coefficient of risk factors

The degree of structural importance denotes the importance of each basic event based on the structure of the fault tree. This study analyzed the structural importance degree of the influence of each collision risk factor on ship collision accidents, which were then sorted, as shown in Table 3. These results were also calculated using Easy Draw.

TABLE 3 Structural importance degrees of navigational risk factors.

Scenario	Risk factors	Structural importance degree coefficient
Ship collision under icebreaker	I[[L6]]; I[[L7]]; I[[L8]]; I[[L9]]	0.86
	I[[L17]]; I[[L18]]; I[[L15]]	0.72
	I[[L12]]; I[[L20]]	0.57
	I[[L23]]; I[[L14]]	0.45
	I[[L10]]; I[[L13]]; I[[L11]]	0.42
	I[[L21]]; I[[L21]]; I[[L19]]	0.37
	I[[L4]]; I[[L2]]; I[[L16]] I[[L3]]; I[[L5]]; I[[L1]]	0.33
Stuck in ice	I[C16]=I[C19]=I[C26]	0.78
	I[C12]=I[C21]=I[C9]=I[C9]=I[C5]=I[C22] =I[C23]	0.32
	I[C4]=I[C27]=I[C10]=I[C17]=I[C28]=I[C6]	0.22
	I[C26]=I[C30]	0.17
	I[C25]=I[C18]=I[C20]	0.12
	I[C24]=I[C7]=I[C11]=I[C13]=I[C15]	0.0625
Ice-ship collision	I[C16]=I[C19]=I[C26]	0.54
	I[C14]=I[C31]	0.41
	I[C12]=I[C3]	0.32
	I[C25]=I[C18]=I[C30]=I[C29]	0.23
	I[C2]=I[C27]=I[C10]=I[C17]=I[C28]=I[C6]	0.12
	I[C24]=I[C1]=I[C11]=I[C32]=I[C13]=I[C15	0.031

Based on the proposed FT model, with the focus on accident scenarios in Arctic ice-covered waters, harsh ice conditions and unsafe supervision were found to have a higher index than others in terms of the degree of structural importance, as can be seen in Table 3. These results show that the latter factors exerted the greatest accident contribution. The results also indicate that environmental factors, such as *ice conditions, ice ridge, poor visibility, snow or rain, ice flow, and icebergs,* contribute to ship accidents in Arctic ice-covered waters, with highest of the structural importance degree coefficient. These are followed by the risk factors of unsafe supervision, such as *over safety speed, drifting with ice, and improper route selections,* with higher structural importance degree coefficient. The structural importance degree coefficients of the above navigational risk factors are higher in typical Arctic accident scenarios, indicating that these navigational risk factors have a great impact on the safety of navigation in these waters. Meanwhile, the structural importance degree coefficients of the other factors were found to be lower, indicating that they, in turn, exert a lower impact on safe navigation, but that they also contribute to shipping accidents in Arctic ice-covered waters.

4.4 Relationship analysis of different accident scenarios

In this chapter, various approaches were used to identify the navigational contributing factors in Arctic ice-covered waters, with the focus on ships under icebreaker assistance and ships traveling independently, and with reference to accident reports, expert knowledge, and scientific literature. The analysis of navigational risk factors was carried out using a fault tree analysis based on the accident procedure. Following this, the navigational risk factors were qualitatively analyzed using the structural importance degree coefficients and the minimum cut sets based on the accident scenarios. Finally, the structural importance degree coefficients of the navigational risk factors in different accident scenarios and the analysis results mentioned in the accident reports were compared, as shown in Fig. 11. This comparison indicates that the structural importance degree coefficients are closely related to real-life situations. The analysis found some differences and commonalities among these navigational risk factors contributing to three typical accident scenarios. The comparative analysis of these risk factors is shown in Fig. 11, which could provide theoretical guidance for RCOs focusing on typical accident scenarios.

5 Discussion and conclusion

The analysis in this chapter provides key ship performance and management indicators for ice navigation. The comparative analysis of navigational risk factors is shown in Fig. 11, with the focus on three typical accident scenarios. This research resulted in the identification of 37 navigational risk factors of three typical accident scenarios, using HFACS and the text mining approach based

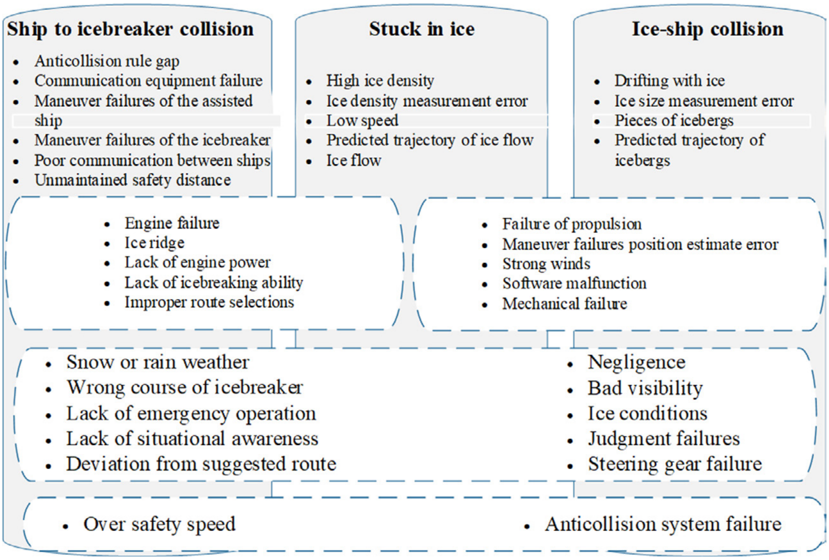

FIG. 11 Comparative analysis of navigational risk factors in different scenarios.

on accident reports and the scientific literature. FT models were established for different accident scenarios based on the historical accident procedure. In addition, a qualitative analysis of typical accident risk factors was carried out, which contained a minimum cut set analysis and the calculation of structural importance degree coefficients. The results of this research capture the actual aim accurately, and the corresponding RCOs are proposed to prevent accident occurrence in Arctic ice-covered waters.

The uncertainties in the conclusions will be taken into consideration as follows: Inaccuracies in data, assumptions made about the model, and modeling procedures are conditions or choices that may affect the conclusions. The navigational risk factors in this study were identified using a reliable approach based on accident reports and scientific literature. While the number of accident reports was insufficient, the FT modeling and the qualitative risk analysis were further complemented with experts' knowledge, and the results show concordance with real-life situations. Thus, the uncertainty assessment of approach and model is high, the data of this research is medium, and the assumption is low. Above all, the FT model relies on historical accident procedures that are formulated in a specific format; therefore, additional accident reports could reduce the uncertainty of FT modeling, which could be a point of improvement in future research.

This chapter provides a comprehensive analysis of navigational risk factors, with a focus on three typical accident scenarios. First, the 37 navigational risk factors are identified using the HFACS-based ship collision risk analysis model and test mining approach based on accident reports and scientific literature.

Then, the fault tree analysis is utilized to identify the fundamental risk factors contributing to three typical accident scenarios based on the historical accident procedure. Finally, qualitative analysis is carried out to analyze navigational risk factors, where the compared analysis is formulated for three typical accident scenarios, which could provide theoretical guidance for RCOs. Overall, and notwithstanding the model assumptions, the comparison of the qualitative analysis results and historical accidents shows that the results obtained by the qualitative analysis based on the FTA are in agreement with real-life situations. Thus, the results obtained can be seen as promising, and as potentially able to aid further understanding of key navigational factors in Arctic ice-covered waters.

Appendix

- Cut sets for typical accident scenarios are shown as follow:

Minimum cut sets of the FT for collision accidents under icebreaker assistance
{L17,L19,L21,L22}； {L1,L3,L5,L13}； {L1,L3,L5,L11}; {L10,L12,L20}； {L2,L4,L10,L16}； {L12,L13,L20}； {L2,L4,L13,L16}； {L11,L12,L20}； {L2,L4,L11,L16}； {L6,L8,L14,L23}； {L6,L8,L15}； {L6,L8,L17}； {L7,L8,L14,L23}； {L7,L8,L15}； {L7,L8,L17}； {L6,L9,L14,L23}； {L6,L9,L15}； {L6,L9,L17}； {L7,L9,L14,L23}； {L7,L9,L15}； {L7,L9,L17}； {L18,L19,L21,L22}； {L6,L8,L18}； {L7,L8,L18}； {L6,L9,L18}； {L7,L9,L18}; {L14,L19,L21,L22,L23}； {L1,L3,L5,L10}； {L19,L21,L22,L15}
Minimum cut sets of the FT for ship stuck in ice
{C4,C16,C19,C12,C26};{C24C7,C11,C13,C15};{C25,C29,C14,C22,C23};{C10,C16,C19,C12,C26};{C27,C16,C19,C12,C26};{C16,C19,C12,C26,C6};{C17,C16,C19,C12,C26};{C28,C16,C19,C12,C26};{C4,C16,C19,C21,C26};{C4,C16,C19,C26,C24};{C4,C16,C19,C26,C5};{C10,C16,C19,C21,C26};{C10,C16,C19,C26,C24};{C10,C16,C19,C26,C5};{C27,C16,C19,C21,C26};{C27,C16,C19,C26,C24};{C27,C16,C19,C26,C5};{C16,C19,C21,C26,C6};{C16,C19,C26,C6,C24};{C16,C19,C26,C6,C5};{C17,C16,C19,C21,C26};{C17,C16,C19,C26,C24};{C17,C16,C19,C26,C5};{C28,C16,C19,C21,C26};{C28,C16,C19,C26,C24};{C28,C16,C19,C26,C5};{C18,C29,C14,C22,C23};{C20,C29,C14,C22,C23};{C30,C25,C14,C22,C23};{C30,C18,C14,C22,C23};{C30,C20,C14,C22,C23}
Minimum cut sets of the FT for ice-ship collision in ice
{C2,C16,C19,C26,C12};{C24,C1,C11,C32,C13,C15};{C25,C30,C14,C31};{C10,C16,C19,C26,C12};{C27,C16,C19,C26,C12};{C16,C19,C26,C12,C6};{C17,C16,C19,C26,C12};{C28,C16,C19,C26,C12};{C2,C16,C19,C26,C3};{C10,C16,C19,C26,C3};{C27,C16,C19,C26,C3};{C16,C19,C26,C3,C6};{C17,C16,C19,C26,C3};{C28,C16,C19,C26,C3};{C18,C30,C14,C31};{C25,C29,C14,C31};{C18,C29,C14,C31}

Note: The cut set in a fault tree is a set of basic events whose (simultaneous) occurrence ensures that the TOP event occurs, and the minimum cut set denotes that a cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set.

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