Use of HFACS and Fault Tree Model for Collision Risk Factors Analysis of Icebreaker Assistance in Ice-covered Waters

Mingyang Zhang[1, 2,3], Di Zhang[1, 2]*, Floris Goerlandt[3,4], Xinping Yan[1, 2], Pentti Kujala[3]

(1 Intelligent Transportation Systems Research Center, Wuhan University of Technology, China

2 National Engineering Research Center for Water Transport Safety, MoST, Wuhan University of Technology, China

3 School of Engineering, Department of Mechanical Engineering, Marine Technology, Aalto University, Espoo, Finland)

4 Dalhousie University, Department of Industrial Engineering, Halifax, Nova Scotia B3H 4R2, Canada

(*Corresponding at: 1178 Heping Avenue, Wuhan University of Technology, Wuhan, Hubei 430063, P.R. China; Tel: +86-27-86589905; Fax: +86-27-8682280; Email: zhangdi@whut.edu.cn)

ABSTRACT: With the global warming and a large amount of sea ice melting, the available Arctic Sea Route has greatly enhanced the value of Arctic shipping. Ship operations under icebreaker assistance have become an essential way to facilitate the safe navigation of merchant vessels sailing through the Arctic Sea Route in ice-covered waters, but they can also put the crew and the ship in danger caused by a possible collision between the assisted ship and the icebreaker. In this paper, a dedicated Human and Organizational Factors (HoFs) model of ship collision accidents between an assisted ship and an icebreaker is developed and analyzed with the aim to identify and classify collision risk factors. First, a modified model of the Human Factors Analysis and Classification System (HFACS) for collision accidents between a ship and an icebreaker in ice-covered waters is proposed, which helps to analyze ship collision reports. Then, a Fault Tree Analysis (FTA) model is utilized to analyze the fundamental collision risk factors according to the statistical analysis of accident reports and expert judgments based on the HFACS-SIBCI model. Finally, qualitative analysis is carried out to analyze collision risk factors under icebreaker assistance, where Risk Control Options (RCOs) are formulated. An important guidance for the risk control of ship collisions during icebreaker assistance in ice-covered waters is provided for lawmakers and shipping companies.

Keywords: Arctic shipping, Collision accidents, Ship to icebreaker, HFACS, FTA

1. Introduction

With the global warming and a large amount of sea ice melting, the extremely valuable Northern Sea Route (NSR) has led to an increased interest in Arctic activities of ships (Beveridge., 2016; Fu et al., 2017). In this area, navigational operations under icebreaker assistance are key to the success of the safe navigation of merchant vessels (Zhang et al., 2017; Montewka et al., 2015; Valdez Banda et al., 2015). It is very difficult to ensure the safety of navigation in Arctic waters when vessels sail independently facing 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., 2017; Ostreng et al., 2013). At the same time, ordinary vessels lack the capability of ice-breaking, so they are unable to sail independently in a harsh ice environment, which can easily lead to ice accidents (Kum et al., 2015; Zhang et al., 2017; Fu et al., 2016). Hence, navigational operation under icebreaker assistance represents a typical model of ship operation in ice-covered waters. In 2016, 62.5% of General Cargo Carriers were under icebreaker assistance in the ice-covered waters of the NSR which provided by Northern Sea Route Information Office (Transit Statistics 2011–2016). In addition, icebreaker assistance operations also play an essential role in the ice-covered waters of the Baltic Sea in winter. The numbers of vessels under icebreaker assistance during the icebreaking season in the Baltic Sea in different years are shown in the following picture taken from *Baltic Sea Icebreaking Report 2007-2016* provided by the *Baltic Organization*.

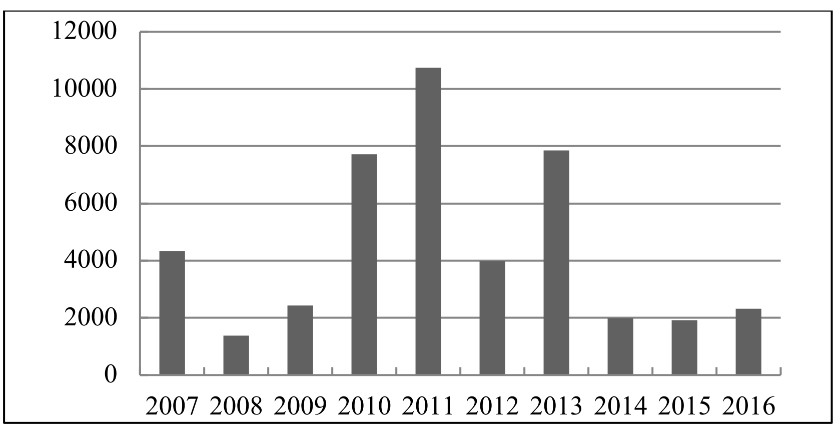

Figure 1. The number of assisted ships under icebreaker assistance in the Baltic Sea in wintertime (2007-2016). Source: Baltic Sea Icebreaking Report (2007-2016)

Icebreaker assistance is a widespread method used in navigation in ice-covered waters. Navigational operations under icebreaker assistance are organized into four identified icebreaker operations: *Escort operations, Convoy operations, Breaking a ship loose operations* and *Towing operations* (Goerlandt et al., 2017; Valdez Banda et al., 2015), where escort operations and convoy operations are key to the success of the safe navigation of merchant ships. Convoy operations are similar to escort operations, where several ships follow an icebreaker at a short distance in case the ice channel is filled with ice cakes (Zhang et al., 2017). Escort and convoy operations under icebreaker assistance reduce the risk of frequent accidents, such as ice collisions and propeller or rudder damage. Nevertheless, collision accidents do occur between icebreakers and assisted ships. The statistics of accidents occurred in ice-covered waters of Russian sea area (Goncharov et al., 2011; Loanov et al., 2013) and Finnish sea area (Valdez Banda O.A. 2017) are presented in Figure 2. It can be seen that in Finnish sea area the percentage of collisions is 48% out of all accidents, and 95% out of all accidents under icebreaker assistance. In addition, in Russian sea area, collisions during escort operation account for 55% under similar assistance conditions. Despite the differences between Finnish and Russian sea areas, the statistics of accidents indicate that ship to icebreaker collision is the most typical accident type in ice-covered waters.

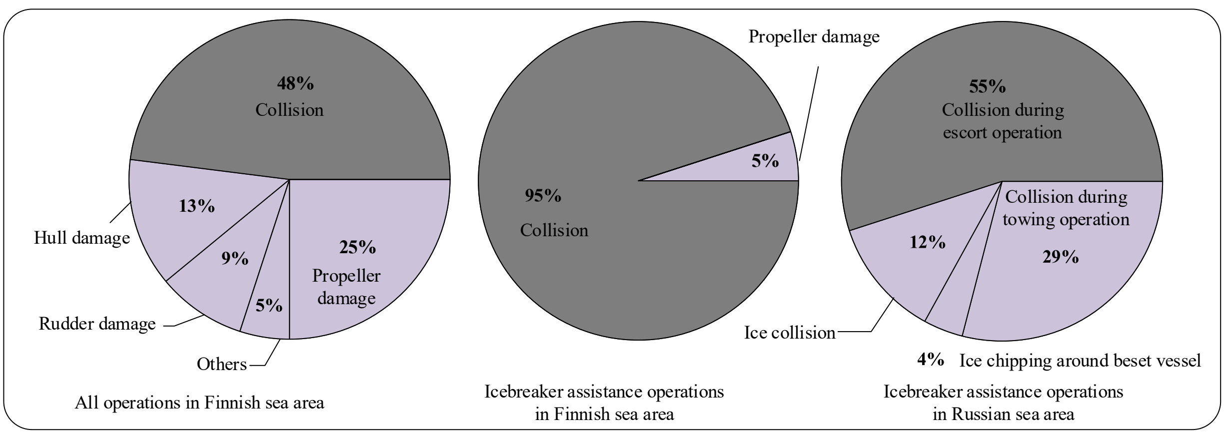

Figure 2. The statistics of accidents occurred in ice-covered waters in Russian Sea area (Goncharov et al., 2011; Loanov et al., 2013) and Finnish Sea area (Valdez Banda O.A. 2017)

Collision risks between icebreakers and assisted ships sailing within a close distance cannot be ignored in ice-covered waters. In the scientific literature, the risks of collisions under icebreaker assistance are 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, collision risk factors should be investigated under specific conditions. There exists literature on accidents analysis in open waters and ice-covered waters. The risks of ship collisions are assessed, which is of signification importance for narrow, shallow and busy waterways (Qu et al., 2011; Klanac et al., 2010; Zhang et al., 2016). 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 operations performed in the ice-covered waters. Overall, collisions between assisted ships and icebreakers present the most significant risk (Valdez Banda et al., 2016; Goerlandt et al. 2017). A root cause analysis method is presented to analyze the risks of collisions and grounding in Arctic waters, which aims at proposing a recommendation to reduce the occurrence probability based on fuzzy fault tree analysis (Kum et al., 2015). An Arctic shipping accident scenario is analyzed to identify essential accident risk factors in a potential accident scenario (Afenyo et al., 2017). Risk analysis models of ships stuck in ice are proposed (Fu et al., 2014, 2016; Montewka et al., 2015). Another line of work focuses on the application of risk-based design principles to Arctic shipping (Bergström et al. 2015, Ehlers et al. 2017).

However, these studies are limited in terms of the risk analysis of typical operational conditions or accidents, such as collisions between ships or a ship and ice, grounding accidents, and ship stuck incidents in ice-covered waters, not focusing on collision risk factors during icebreaker assistance operations in ice-covered waters.

Icebreaker assistance operations in ice-covered waters refer to a team navigation system consisting of an icebreaker and an assisted ship. The detuning of the navigational conditions between the icebreaker and the assisted ship is the cause of a collision accident after a change in the team navigational system. Accordingly, human and organizational factors are main factors contributing to the occurrence of collision accidents. In the scientific literature, a number of human error analysis models and frameworks have been proposed to aid in the understanding of faults and errors related to human and organizational factors in complex systems where such accidents occur, such as the four stage information processing model presented by Wickens et al. (1988), the SHEL model (Edwards, 1972), the multiple SHEL model (IMO, 1999), and the GEMS (Generic Error Modeling System) proposed by Reason et al. (1990). These models and frameworks focus on the human errors of operators.

The framework of the Human Factors Analysis and Classification System (HFACS) was presented by Wiegmann et al., 2003, which was used to classify and identify contributing factors in accident factors analysis. The HFACS-framework was used to analyze maritime accidents (Chauvin et al., 2013; Chen et al., 2013), potential impact of unmanned vessels on marine transportation safety (Wróbel et al., 2017), grounding accidents (Mazaheri et al., 2015), road traffic accidents (Baysari et al., 2008; Reinach et al., 2006; Patterson et al., 2010), railway accidents (Zhan et al., 2017), and classify and identify fundamental risk factors based on accident reports.

In particular, a systematic and multi-factorial analysis of collision factors under icebreaker assistance is presented, which aims at identifying and classifying collision risk factors. The research relies on the HFACS and the FTA, which are utilized to identify and classify collision risk factors that are mentioned in reports of accidents between icebreakers and assisted ships in ice-covered waters. First, a collision risk factors analysis method for ship collision accidents between assisted ships and icebreakers in ice-covered waters, named the HFACS-SIBCI model, is proposed. Then, a Fault Tree model is proposed using the statistical analysis of collision risk factors according to accident reports and expert knowledge. Finally, a qualitative analysis is carried out to analyze collision risk factors using structural importance degree coefficients and minimum cut sets, which provides a theoretical basis for the formulation of risk control strategies.

The rest of this paper is organized as follows. Section 2 describes the research methodology and data along with the problem statement. The model development and results are presented in Section 3. Section 4 and Section 5 presents our discussions and conclusions.

2. Method and data

According to accident statistics and scientific literature, accidents caused by human and organizational factors (HoFs) account for 90% of the total number of maritime accidents (Chauvin et al., 2011; Hetherington et al., 2006). At the same time, the lack of system coordination after detuning the navigational conditions between the icebreaker and the assisted ship resulting from human and organizational factors without effective Risk Control Options (RCOs) leads to ship collision accidents. Therefore, human errors and hidden organizational factors play vital roles in the ship collision risk factors classification and identification under icebreaker assistance and proposed RCOs. In view of this, this paper proposes a HFACS-based framework of ship collision risk factors under icebreaker assistance to solve the problem of the identification of human and organizational factors in ship collision risk factors classification under icebreaker assistance. Further, an FT model is utilized to analyze fundamental risk factors. We discuss the initial framework of the HFACS and the FTA method in what follows. The research flowchart is presented in Figure 3.

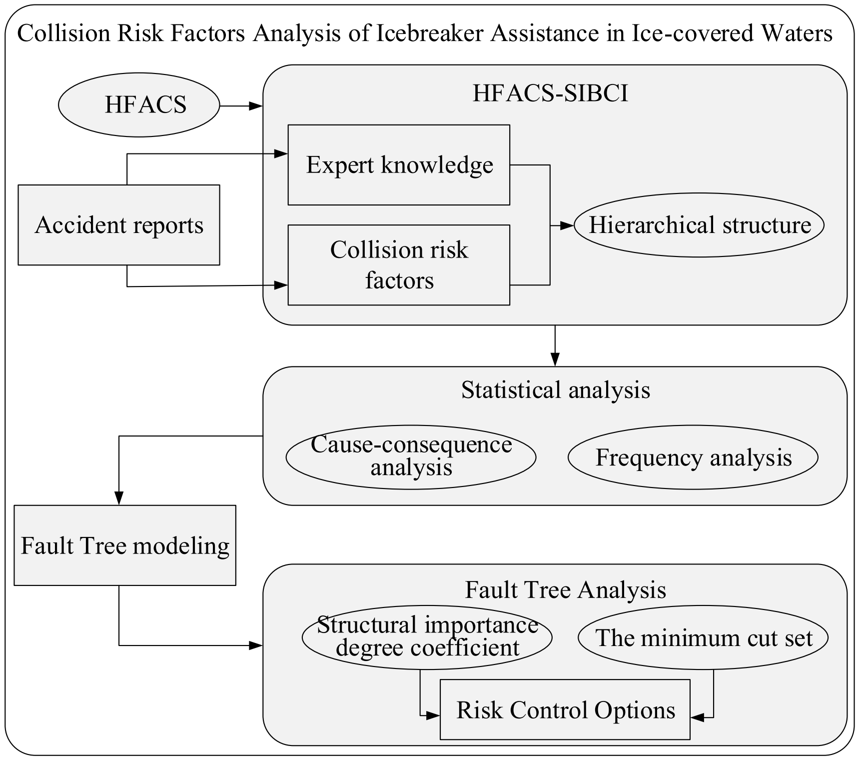

Figure 3. The flowchart of the collision risk factors analysis of icebreaker assistance in ice-covered waters.

2.1 The HFACS framework

The initial Human Factors Analysis and Classification System (HFACS) framework consists of four layers: *organizational factors*, *unsafe supervision*, *preconditions for unsafe acts*, and *unsafe acts,* which is proposed by Wiegmann et al., 2003. Reinach and Viale (2006) proposed a fifth layer, *External factors*. They believed that the identification of accident risk factors should consider the economy, law and policy as a supplement in the HFACS. Chauvin et al. (2013) developed a model to analyze human and organizational factors in maritime accidents using the five layers of the HFACS. The framework of the modified HFACS with five layers is proposed to classify and identify accident-contributing factors using accident reports and incident reports. In these applications of the HFACS framework to specific contexts, the contributing factors of each layer are interpreted in specific situations considering accidents. Overall, the HFACS framework has been convincing for risk assessment and risk analysis, where the factors of each layer change continuously according to the research object. Moreover, HFACS-Ship-Icebreaker Collision in Ice-covered waters (HFACS-SIBCI) is proposed to identify and classify the collision risk factors during icebreaker assistance based on the initial HFACS framework.

2.2 Fault tree analysis

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 was used to establish effectively and clearly relationships among accident risk factors using LNG ship accident analysis (Zhou et al., 2017), ship grounding in Arctic (Kum et al., 2015), explosion of crude oil tanks (Wang et al., 2013). Moreover, the FTA can reproduce the evolution of underlying factors and high-level accidents, which helps to understand the development course of collision accidents and provide guidance for the formulation of RCOs.

In FT model, after the identification and classification of collision risk factors under icebreaker assistance, this paper further explores the causes and consequences of accidents by analyzing the relationship between collision risk factors and collision accidents using the FTA. At the same time, collision accidents are qualitatively analyzed based on the structural importance degree coefficient and the minimum cut sets of the FTA. The essence of the FTA is to establish logical relationships among factors based on the mathematical logic theory. Logical relationships are OR and AND gates. Logical sum is represented by the OR gate. Logical product is represented by the AND gate. The formulas are shown in equations (1) and (2).

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

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

where $\varphi(x)$ and $\phi(x)$ are the top event used to describe the complex system state; and x_i are 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 qualitative analysis, the probabilities of risk factors are assumed equal. At the same time, the institutional importance of all risk factors is calculated using the minimum cut sets of the proposed FT. In addition, the structural importance degree of the FT is calculated. Structural importance degree denotes the importance of each basic event from the structure of fault tree. In the paper, the probabilities of all ship collision risk factors under icebreaker assistance are assumed equal. Then, the influence of the upper event on the top event is analyzed, and the results are sorted according to the structural importance degree. Finally, the RCOs can be developed according to the structural importance degrees obtained by the qualitative analysis using the proposed FT for ship collision accidents under icebreaker assistance in ice-covered waters. There are generally two ways to calculate the structural importance degree of the FT: (i) one is to calculate the structural importance degree coefficient, and (ii) the other is to use the minimum cut sets for judgment.

(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 a basic event changes (usually from normal operation to failure), the system may have 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 failure state $\{(1)\}$;
- The system changes from a failure state to normal operation $\{(1) \rightarrow (0)\}$;

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

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

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

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

This method has the following three criteria used for judgment:

- When the numbers of basic events in the minimum cut sets are different, individuals with fewer basic events are more structurally important.
- When the numbers of basic events in the minimum cut sets are equal, basic events having high occurrence frequencies are more structurally important.
- Basic events with fewer occurrences in minimum cut sets are generally more structurally important. The structural importance degree of two events is equal in rare cases.

In view of uncertainties in factors influencing ship collision risks under icebreaker assistance, the fault tree analysis method can be used to analyze ship collision accidents by combining ship collision accident based on the statistical analysis of ship collision risk factors under icebreaker assistance.

2.3 Collision accident reports

Official accident reports play an essential role in risk factors analysis and being analyzed by an accident investigation board usually present valuable and detailed information about accidents (Mazaheri et al., 2015). We processed 17 accident reports on ship collision accidents between icebreakers and assisted ships in ice-covered waters, which contain the whole process of collision accidents in detail and accident investigation results. We utilized 14 ship collision reports on icebreaker assistance selected from *Swedish Accident Investigation Board (SHK)*, two collision reports from the UK *Marine Accident Investigation Branch (MAIB)* and one collision report from Russian *FleetMon.* A total of 17 accidents during 1989-2017 freely accessible to the public were analyzed using the proposed approach. 16 collision reports contain detailed information including the summary, general description of the ship, external conditions and conclusion of the investigation that occurred in the Baltic Sea. One collision report only described the process of the collision accident. A total of 17 accident reports are analyzed shown in Appendix A. In this paper, the 17 accidents during 1989-2017 are used for detailed analysis. Only the collision risk factors mentioned in the accident reports are considered and further classified based on the proposed model.

3. Model and results

The proposed collision factors analysis procedure can be briefly divided into three stages: (i) Collision factors identification and classification using HFACS-SIBCI and (ii) Fault tree analysis. The model development and results are described as follow.

3.1 HFACS-SIBCI

3.1.1 Analysis on risk factors of ship collisions under icebreaker assistance

The HFACS-based ship collision risk analysis model of the HFACS-SIBCI (HFACS-**S**hip-**I**ce**b**reaker **C**ollision in **I**ce-covered waters) is established to classify and identify ship collision factors. The HFACS-SIBCI model consists of five ship collision risk analysis levels and 28 classification categories, as shown in Figure 3. The HFACS-SIBCI is established as a five levels framework, which is similar to the HFACS-Coll, HFACS-Grounding and HFACS-MA (Chauvin et al., 2013; Chen et al., 2013; Mazaheri et al., 2015). In particularly, the 28 classification categories contain collision fundamental risk factors affecting collision accidents under icebreaker assistance.

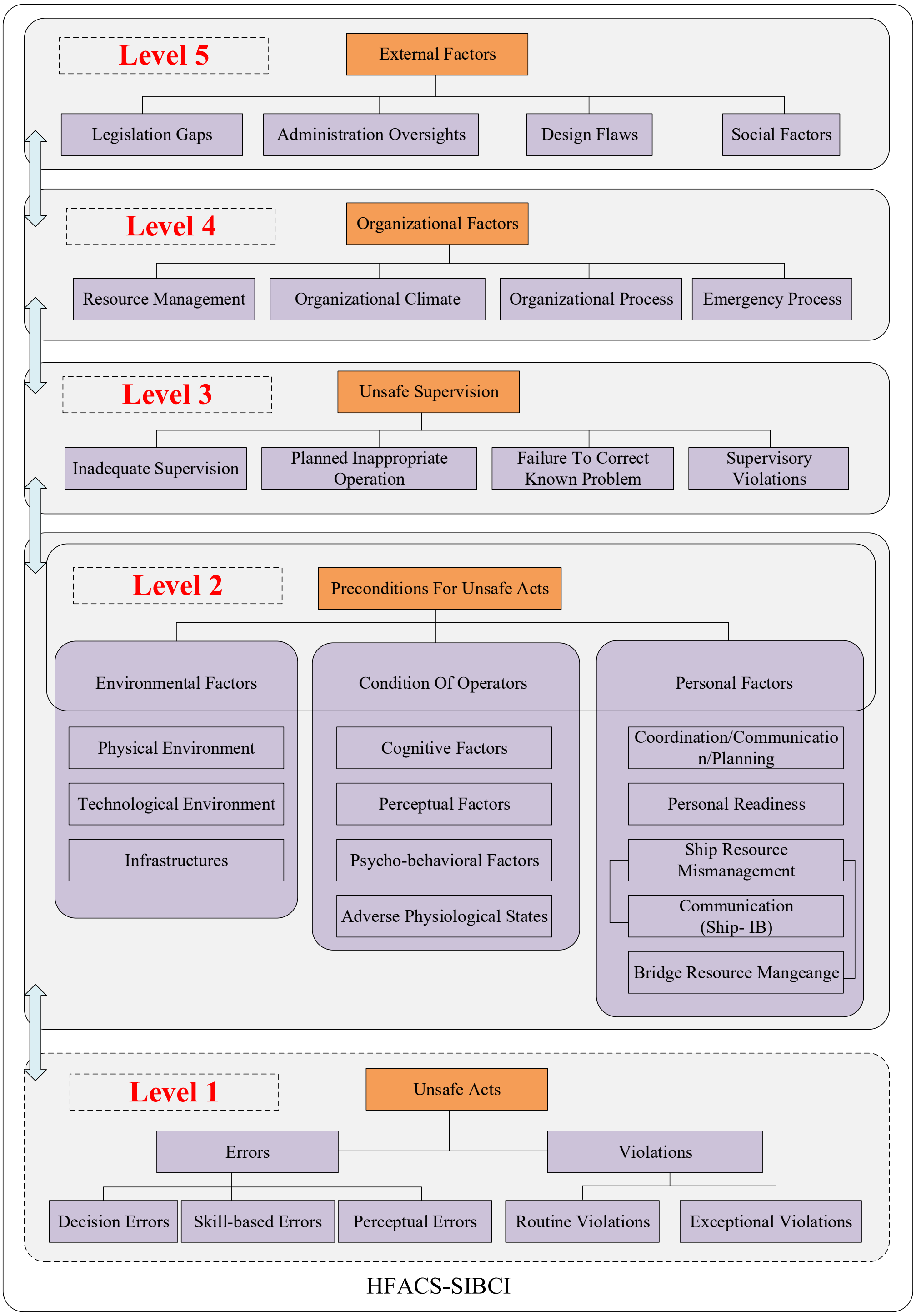

Figure 4. HFACS-SIBCI

The systematic methodology of the HFACS and the corresponding risk factor classification can assist in reducing the shortcomings of the subjective bias, experience restrictions and accident information omission in investigations and analyses of ship collision risk factors under icebreaker assistance in ice-covered waters. Accordingly, this paper constructs the ship collision risk factors identification and classification model of ship collisions under icebreaker assistance using the HFACS-SIBCI model, as shown in Figure 4, to solve the problem of ship collision risks under icebreaker assistance. This paper retains the four original levels of the HFACS framework: *(1) Unsafe acts of the operator; (2) Preconditions for unsafe acts; (3) Unsafe supervision; (4) Organizational factors*, and supplements them with *(5) External factors* causing icebreaker-ship collision accidents during icebreaker assistance; and further proposes the HFACS-SIBCI model with five levels.

In this paper, in order to establish collision risk factors classification, the collision accident risk factors analysis model is presented based on the HFACS-SIBCI. The contributing factors mentioned in the accident reports is identified as risk factors, which is described as followed. First, ship collision risk factors under icebreaker assistance are identified using the five-layer HFACS-SIBCI model. The classification model is utilized to classify ship collision factors based on the classification categories that contain the five collision risk analysis levels, and 28 classification categories, such as *decision errors*, *technical errors*, *legislation gaps* and so on. The HFACS-SIBCI accident risk factors classification model is shown in Figure 5, which is different from the HFACS-Coll, HFACS-Grounding and HFACS-MA (Chauvin et al., 2013; Chen et al., 2013; Mazaheri et al., 2015; Akhtar et al., 2014).

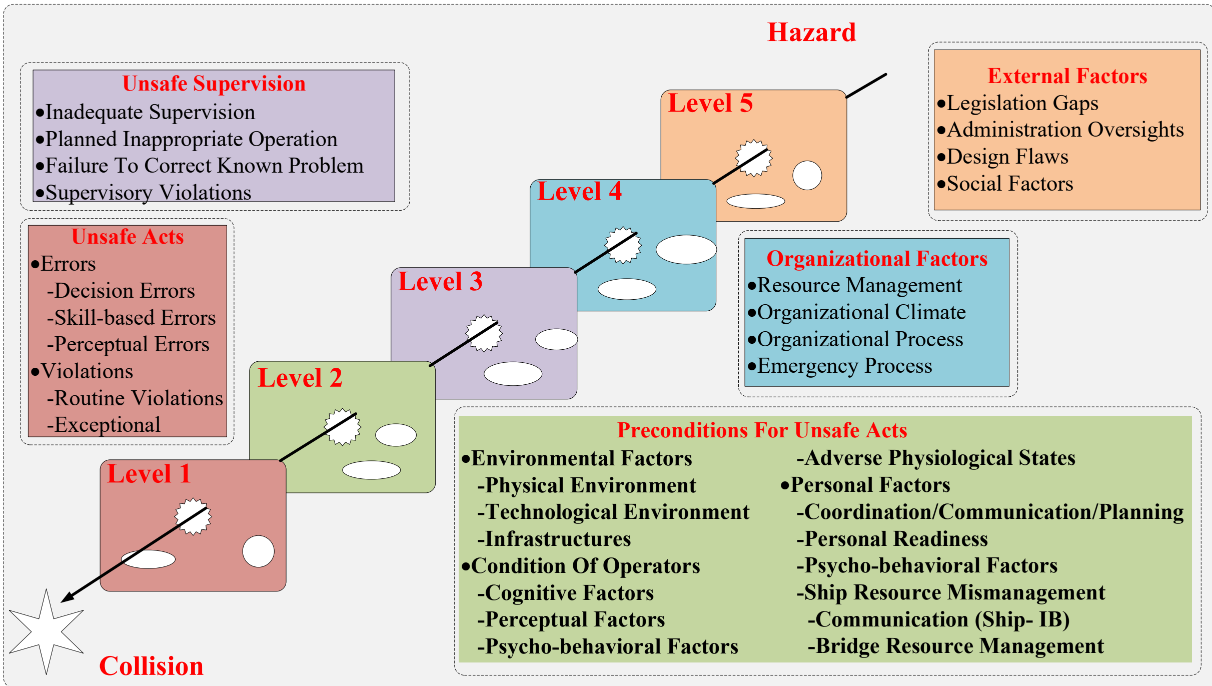

Figure 5. Accident risk factors classification model based on HFACS-SIBCI

In order to classify accurately ship collision risk factors under icebreaker assistance, the understanding of the HFACS-SIBCI accident risk factor analysis model is required. The levels and classification categories are described in Table 1, which can be used to classify the ship collision risk factors as the framework.

Table 1 Description of classification categories of HFACS-SIBCI

Collision risk category		Category description
Unsafe acts	Errors	*Decision errors*: Acts taken according to individual judgment to achieve the desired effect and thereby causing collision accidents in ice-covered waters.
		Skill-based errors: The technical errors of the crew of the icebreaker and the assisted ship due to improper execution procedures, inadequate training or low proficiency.
		Perceptual errors: The occurrence of a ship collision accident under icebreaker assistance due to misunderstanding or misjudgment.
	Violations	*Routine violations:* Rules and instructions are frequently ignored, in particular by the icebreaker. The assisted ship should also follow the orders of the icebreaker (IMO).
		Exceptional violations: The operating procedures or prescribed actions are violated by the crew, in general, as a result of unskilled technology.
Preconditions for unsafe acts	Environmental factors	*Physical environment:* Weather and other environmental phenomena, such as the perpetual night and perpetual day, affect the behavior of individuals, resulting in unsafe conditions.
		Technological environment: Failures of equipment or devices cause unsafe conditions, including mechanical failures or damage to equipment necessary for the ship's voyage, steering gear failure, engine failure and anti-collision system failure.
		Infrastructures: Invalid information from ice condition monitoring equipment results in unsafe conditions. Monitoring station location information should also be taken into account.
	Condition of operators	*Cognitive factors:* The perception of the characteristics of the icebreaker assistance operation affects the judgment or behavior of the crews on the assisted ship and the icebreaker, resulting in unsafe conditions.
		Perceptual factors: The occurrence of a ship collision accident leads to misunderstanding or misjudgment, resulting in insecurity.
		Psycho-behavioral factors: These risk factors are caused by the crews' characters or

		psychological problems, psychological barriers, or inappropriate motives.
		Adverse physiological states: Physiological events causing low performance, such as lack of sleep, dizziness caused by ice-covered conditions, the perpetual night and perpetual day etc.
	Personal factors	*Coordination/communication/planning:* Ineffective communication between the icebreaker and the assisted ship due to a language barrier, misunderstanding etc.These risk factors influnce assistance operations, emergency operations etc.
		Personal readiness: The officers of the shipping company ignore the rules and instructions on individual abilities, or make poor judgments in preparation for the execution of the task.
		Ship resource mismanagement: The crews of the icebreaker or the assisted ship fail to make accurate judgment regarding the full use of equipment, resulting in an unsafe situation.
Unsafe supervision	Inadequate supervision	Supervision is inappropriate or improper, which makes it impossible to identify and control risks, and to provide guidance and training regarding situations.
	Planned inappropriate operation	Supervision fails to assess adequately risks associated with the actions of non-proficient or inexperienced personnel, who are allowed to carry out tasks beyond their capabilities, especially on the assisted ship.
	Failure to correct known problem	Supervision fails to correct problems and unsafe acts, even though these problems are clear.
	Supervisory violations	Supervision intentionally ignores orders, guidance, rules or operating instructions, such as by breaking safety speed and distance rules set according to Sailing Directions.
Organizational factors	Resource management	The allocation of resources directly or indirectly affects the safety of the icebreaker assistance operation, being unsafe under wrong management.
	Organizational climate	Individual behavior is affected by the organizational environment, structure, policies and cultures, which may result in an unsafe situation.
	Organizational process	Organizational operations and systems may adversely affect individuals, supervisory or organizational performance.
	Emergency process	The organization fails to develop an effective contingency strategy, leading to insecurity. There is no emergency training involving the icebreaker and the assisted ship during the assistance operation in ice-covered waters.
External factors	Legislation gaps	Differences in international and national ice ship navigation regulations and policies affect icebreaker assistance operations, which may lead to poor management or unsafe acts of operators. For example, Russia (Sailing Directions of Russia), Finland (Finnish Transport Agency), Canada (Transport Canada) and China (Guidance on Arctic Navigation in the Northeast Route) have respective Arctic navigation rules, where navigation regulations are different.
	Administration oversights	The icebreaking service company, shipping company or ship officers have defects in rules or codes, or neglect their duties.
	Design flaws	The design of the icebreaker or the assisted ship is flawed, so the ability to navigate in Arctic ice areas is poor.
	Social factors	Economic, political, legal, safety culture and other social environmental factors.

3.1.2 Ship collision risk factors classification and hierarchical structure model

Icebreaker assistance operations are typical team operations in ice-covered waters involving icebreakers and assisted ships sailing in complex environments with harsh weather conditions. Ship collision accident reports under icebreaker assistance in ice-covered waters and accident research literature are analyzed according to experts' knowledge. The collision contributing factors mentioned in the accident reports are considered and classified based on the proposed model. Then, the HFACS-SIBCI model constructed in Section 3.1.1 is used to classify and identify the collision risk factors, namely, *External factors, Organizational factors, Unsafe supervision, Preconditions for unsafe acts* and *Unsafe actors*, of the navigational system in ice-covered waters. At the same time, the hierarchical structure of ship collision risk factors is constructed based on the HFACS-SIBCI.

We classify ship collision accidents between icebreakers and assisted ships and establish the hierarchical structure of ship collision risk factors. The collision risk classification procedure is presented as follows. First, we preliminary select ship collision contributing factors mentioned in the accident reports described in Section 2.3. Second, additional ship collision factors are identified by domain experts, such as *Wrong course of icebreaker* and *Engine failure* in this research. Even if we do not have many accident reports, this way we will not miss ship collision risk factors. At the same time, literature is referenced to check the results regarding ship collisions in open water (Chauvin et al., 2013) and in Arctic ice-covered waters (Kum et al., 2015), as shown in Table 2.

Table 2. Description of ship collision risk factors under icebreaker assistance

	Factors	Description
1	Maneuver failures of the assisted ship	Maneuver failures of the assisted ship cause an unsafe situation during icebreaker assistance.
2	Maneuver failures of the icebreaker	Maneuver failures of the icebreaker cause an unsafe situation during icebreaker assistance.
3	Lack of situational awareness	Uncertainty or unawareness of what is happening regarding the dangerous situation between the icebreaker and the assisted ship, such as the distance between the icebreaker and the assisted ship, speed etc.
4	Negligence	In emergency, the crews fail to take proper actions preventing the process of the unsafe situation.
5	Judgment failures	In emergency, the chosen action is inadequate or wrong, resulting in an undesired state.
6	Ice conditions	Ice conditions ranging from slush ice to solid pack. Ice conditions can be defined by ice concentration, ice thickness and ice type. Such as POLARIS, EGG CODE, etc.
7	Ice ridge	The edge of the ice is superimposed, which is called ice ridge, and it is easy to cause sudden breaking of the icebreaker.
8	Bad visibility	Poor visibility due to fog or snow that influences radar visibility.
9	Snow or rain weather	Hazardous natural environmental phenomena.
10	Engine failure	Mechanical failure related to the power of the icebreaker.
11	Steering gear failure	Mechanical failure related to the control of the course.
12	Anti-collision system failure	Mechanical failure related to the equipment of anti-collision, such as ECDIS, ARPA etc.
13	Communication equipment failure	Mechanical failure related to the equipment of communication between the icebreaker and the assisted ship.
14	Poor communication between ships	Given emergency, there is a communication gap between the icebreaker and the assisted ship regarding cooperative actions. Or there is misunderstanding.
15	Improper route selection	The design of the route makes it hard or dangerous to navigate. Or the severe ice environment influences the navigation system.
16	Wrong course of icebreaker	The icebreaker sails along a wrong course, which causes a collision between the ice edge and the bow of the icebreaker in the ice channel.
17	Over safety speed	The safety speed is the maximum speed when the hull and machine would not be damaged by ice or ship collision when navigating in Arctic ice-covered waters. The speed of the icebreaker and the assisted ship is higher than the safety speed unintentionally, which causes an unsafe situation. Or the speed is so high that the assisted ship cannot stop in a short distance.
18	Unmaintained safety distance	The distance between the icebreaker and the assisted ship is shorter than the standard set by Sailing Directions, which causes an unsafe collision situation.
19	Deviation from suggested	Not being in the planned route or being in a waterway with severe ice conditions

	route	causes an unsafe situation.
20	Lack of emergency operation	Lack of emergency training involving both icebreaker and assisted ship.
21	Lack of icebreaking ability	The icebreaker class is lower than one required by the current ice environment. In particular, the ship's hull is not strong enough. It also is a relative parameter.
22	Lack of engine power	The icebreaker lacks the power to move forward, which causes a sudden break related to the current ice environment. It is also a relative parameter.
23	Anti-collision rule gap	Given emergency, there is no unified ship collision avoidance rule during icebreaker assistance, which results in an unsafe collision situation.

The results on ship collision factors are classified by four experts who have experience to carry out assistance operations in ice-covered waters, according to the five collision risk levels, namely, *unsafe acts, preconditions for unsafe acts, unsafe supervision, organizational factors and external factors*. If more than three classification results of the four experts are consistent, they are adopted. Otherwise, we adopt the classification results of the expert who is always consistent with other experts' results. The format of the questionnaire provided to identify and classify the ship collision risk factors shown in Appendix B. The four experts are described as follows.

- One captain: the captain of a research ship with more than fifteen years' navigation experience in ice-covered waters, including the experience of carrying out icebreaker assistance operations.
- One professor: a professor engaged in navigation safety in Arctic ice-covered waters for more than twenty years, conducting research on communication equipment for navigation in polar conditions.
- Two pilots: each of them with more than five years of experience in icebreaker assistance operations in Bohai Bay of China during wintertime.

When the ship collision factors are classified, the hierarchical structure model of ship collision risk factors is established based on the HFACS framework, as shown in Figure 6.

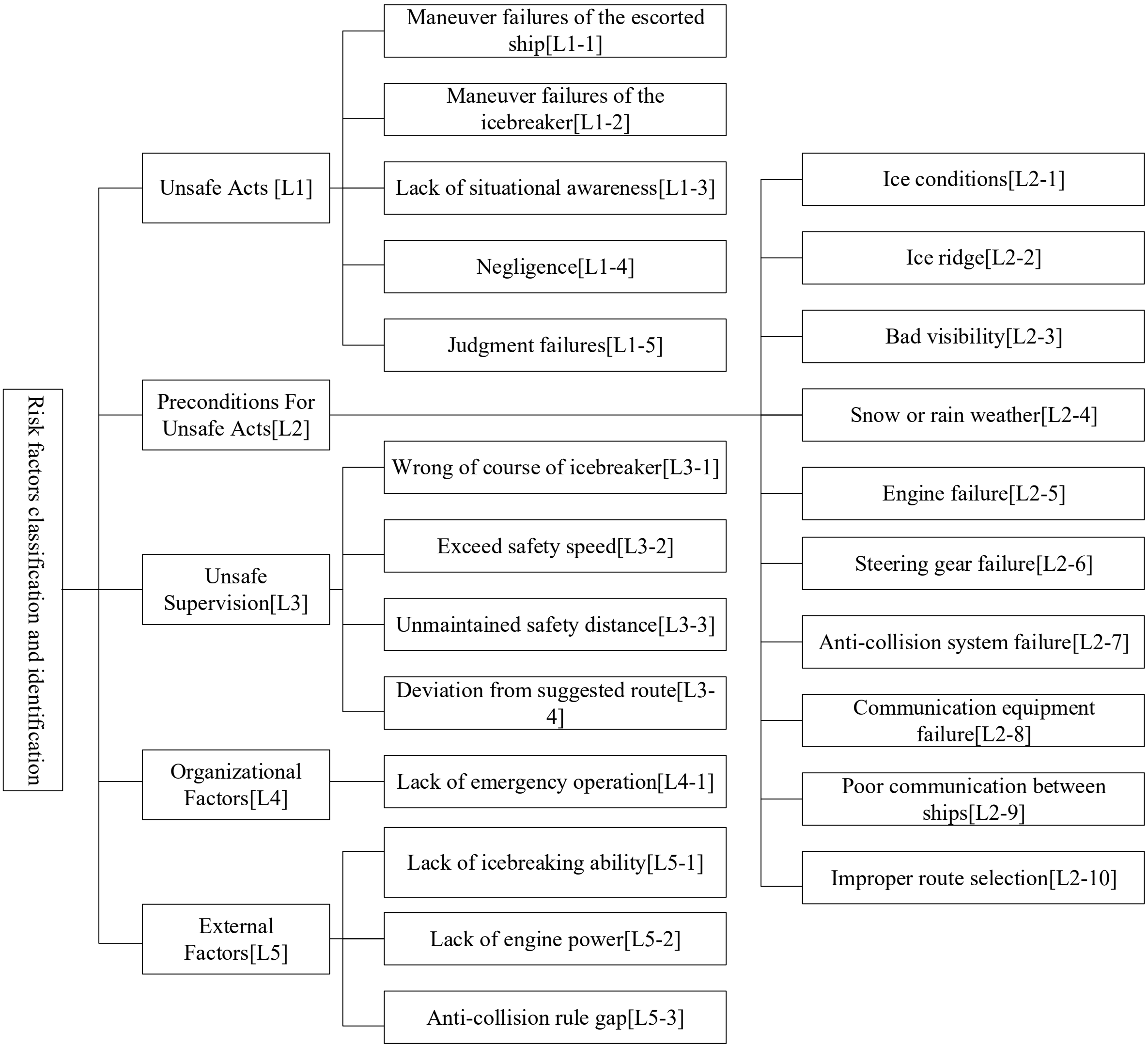

Figure 6. Hierarchical structure of ship collision risk factors

3.1.3 Statistical analysis

Each ship collision accident is caused by many factors, where main contributing factors are different for different accidents. The proposed statistical analysis procedure can be divided into two steps: (i) the contributing collision factors are selected one by one in the 17 accidents, and (ii) hazard situations caused by the contributing collision factors are defined and analyzed, where this step similar to Cause-Consequence Analysis (Chen et al., 2013). At the same time, the consequences, such as hazard situations, caused by the contributing collision factors are elaborated and defined. For example, on 20th of January 2011 at 0057 LT, a ship collision happened between an icebreaker and an assisted ship during an icebreaker assistance operation at 65º05.1'5N, 026º41.0'1E. The icebreaker was damaged to the rubber fender of the towing notch. The escorted ship got a 1.5 m hole in the port bow, and was also damaged to the plating and frames in ice-covered waters. This ship collision accident is analyzed based on the HFACS-SIBCI model according to the two steps shown in Figure 7.

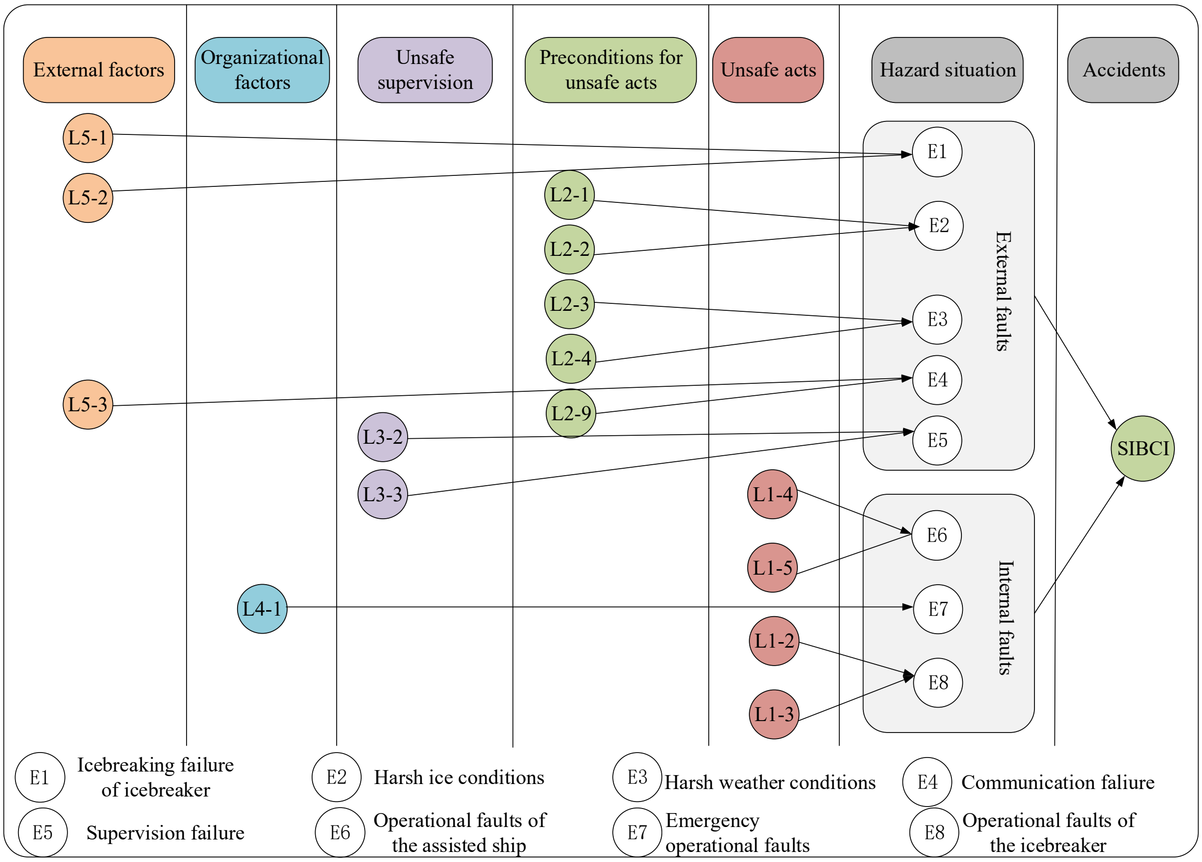

Figure 7. Statistical analysis with HFACS-SIBCI focus on the collision accident

According to the proposed procedure, the statistical analysis of the collision risk factors present in the 17 accidents is conducted according to the accident reports, as shown in Figure 8, and is presented in Appendix A in detail.

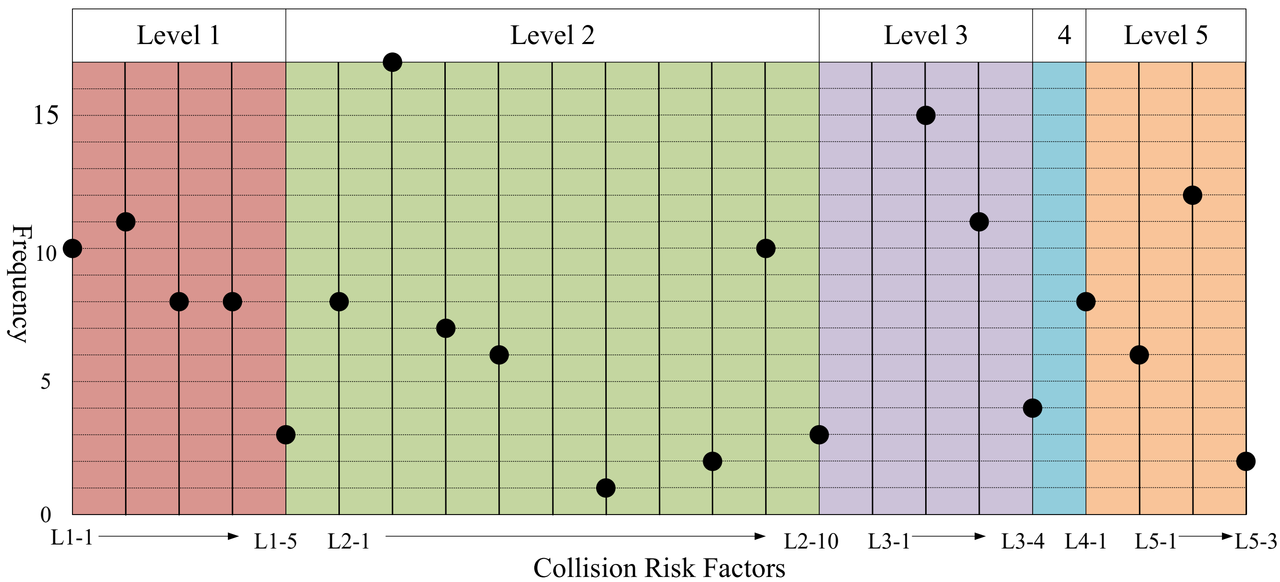

Figure 8. Frequency of collision risk factors under icebreaker assistance (Refer to Table 2 and Figure 6)

The statistics on the occurrence frequency of the corresponding accidents shows that *Preconditions for unsafe acts* and *unsafe acts* exert greater impact on ship collision accidents under icebreaker assistance, where the factor *ice ridge [L2-2]* is related to all 17 accidents. In addition, some collision risk factors are not mentioned in the 17 accident reports, such as *engine failure [L2-5], anti-collision system failure [L2-7] etc.*, but they are also main collision risk factors according to the experts and literature described in Section 3.1.2. So, the frequencies of collision factors are different. But they all can cause ship collision accidents. In brief, the classification and identification of the risk factors of collisions between icebreakers and assisted ships can be realized using the proposed model, which is a basis for the FT modeling of collision accidents.

3.2 Fault Tree modeling of collision accident under icebreaker assistance

3.2.1 FT model

In order to establish the FT model for ship collision analysis under icebreaker assistance, the proposed statistical analysis procedure is carried out to analyze all ship collision accident reports between icebreakers and assisted ships in ice-covered waters. There are many factors that can lead to collision accidents, such as icebreaker failure, harsh ice conditions and communication failures. Collision factors are connected by lower events, so the FT model is established until all branches are terminated with basic factors or intermediate events. Then, we analyze causes and consequences among the ship collision risk factors. At the same time, hazard situations and events are defined according to the statistical analysis using the HFACS-SIBCI, as shown in Figure 7. Accordingly, the preliminary FT is established using the statistical analysis based on cause-consequence analysis of the 17 accident reports. In addition, experts' knowledge is utilized to improve the model by adding ship collision factors that are not mentioned in the accident reports. Finally, the FT modeling is established according to the hierarchical structure model and statistical analysis using the HFACS-SIBCI. The FT model is presented below.

The paper chooses "*Ship collision risk under icebreaker assistance*" as the top event. Then, ship collision risk analysis under icebreaker assistance from the point of view of external and internal failures is considered according to the icebreaker assistance operation mode that is suitable to the procedure of ship collision accidents, as shown in Figure 9.

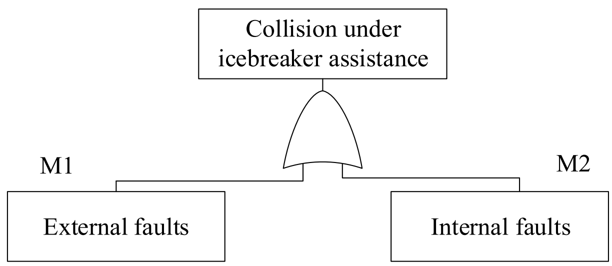

Figure 9 Ship collision risk FT under icebreaker assistance

Due to the large size of the FT for ship collision risk analysis under icebreaker assistance, this paper introduces it from the following two aspects: "*External failure*" and "*Internal failure*".

- FT of "*External failure*" of icebreaker assistance operation

Icebreaker assistance is a complex navigation system involving the external environment, ships (the assisted ships and the icebreaker), crews and coordination. The paper analyzes "*External o*peration errors" and "Unsafe management" according the statistical analysis with HFACS-SIBCI described in Section 3.1.3, and then establishes the FT of external failure of icebreaker assistance operation as shown in Figure 10. Here, M5 is the failure of the icebreaker, M6 stands for harsh navigational conditions, M6 contains two aspects: harsh ice conditions and harsh weather conditions, M7 is communication failure, and M15 is supervision failure. In addition, collision factors are connected by lower events, where the relationships between the factors and events are shown in Figure 7 and Figure 8.

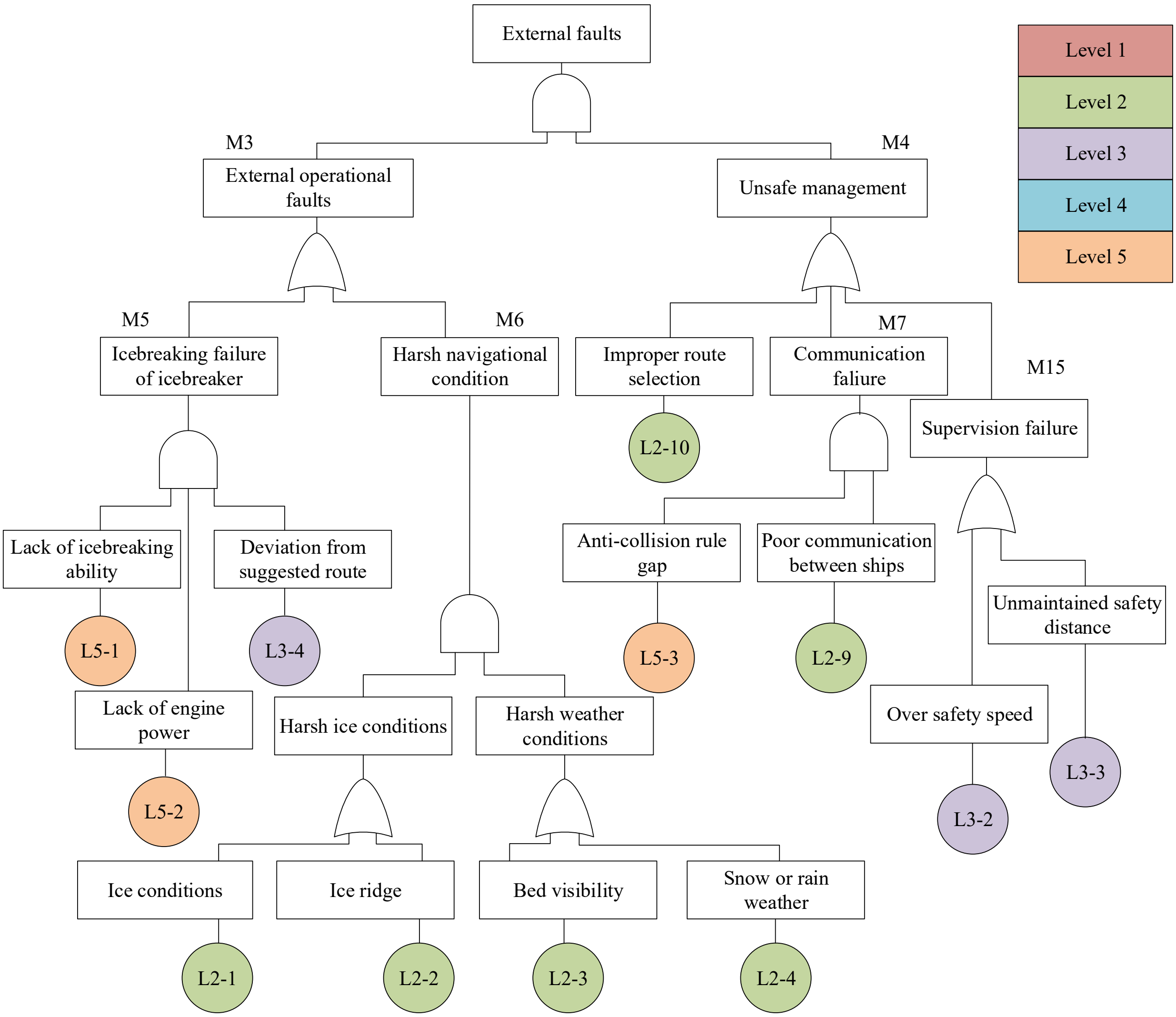

Figure 10. Accident tree of external failure of icebreaker assistance operation

- FT of "*Internal failure*" of icebreaker assistance operation

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

In addition, icebreaker assistance involves many internal failures, so accidents are easily caused by human errors. Accordingly, the FT of internal failure of icebreaker assistance needs to be established based on "*Internal operational faults*" and "*Technical operational faults* " according the statistical analysis with HFACS-SIBCI described in Section 3.1.3, as shown in Figure 11. Here, M10 represents the operation faults of the assisted ship, M11 represents emergency operation faults, and M12 stands for the operation faults of the icebreaker. The relationships among the factors and events are also shown in Figure 7 and Figure 8.

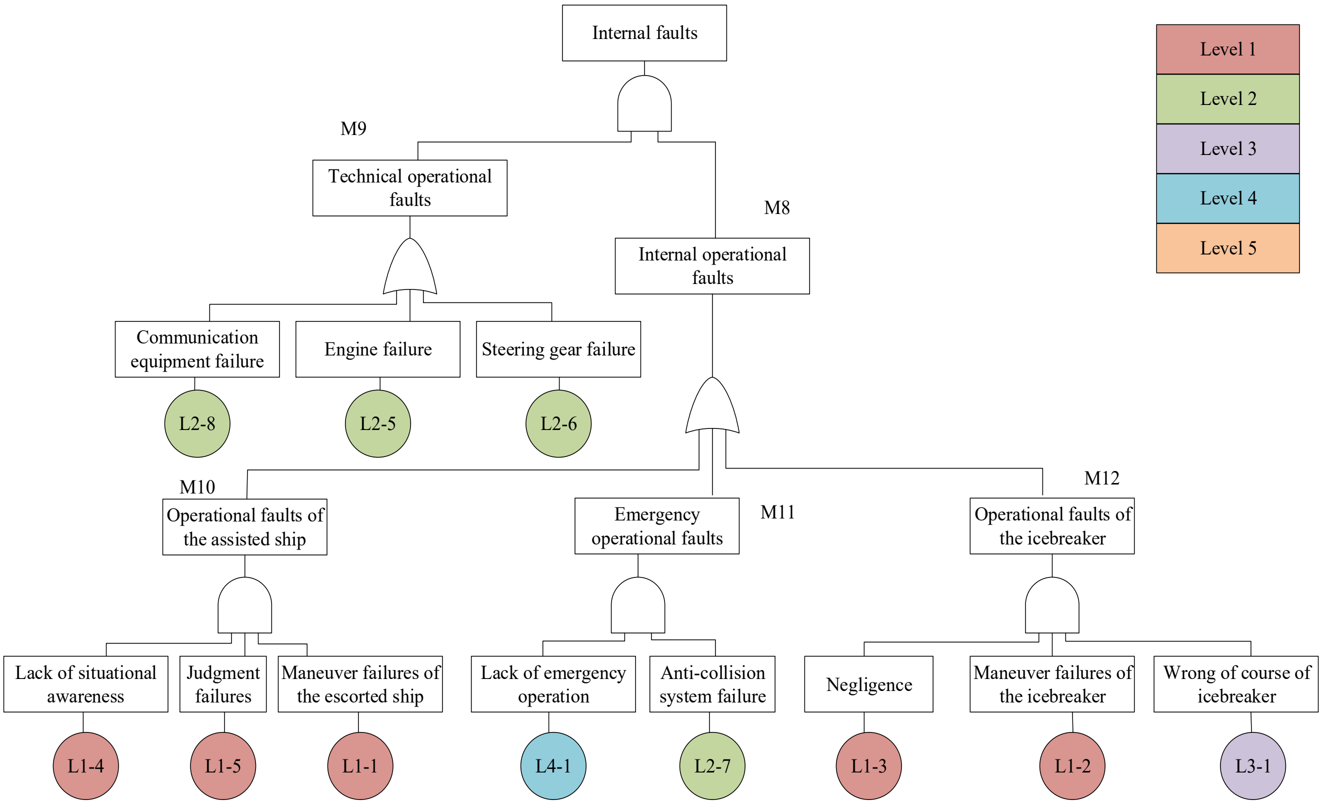

Figure 11. FT of internal failure of icebreaker assistance

3.2.2 Collision risk qualitative analysis

Based on the FT model for ship collision risks under icebreaker assistance, the qualitative analysis of ship collision risk is carried out according to the theory of the qualitative analysis of the FT described in Section 2.2. First, the minimum cut sets of the FT are determined. Then, the structural importance degree coefficients based on the minimum cut sets are calculated and sorted according to their sizes. Further, the corresponding RCOs are proposed to prevent accident occurrence.

(1) The 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, 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. According to logical relationships among the various factors of the FT for ship collision under icebreaker assistance, the minimum cut sets are obtained using the Boolean algebra method (Gupta et al., 1983) and is carried out by software named *Easy Draw (V2.19) (Easy Draw, 2013)*. The results containing 29 minimum cut sets are shown in Appendix C.

The minimum cut sets are obtained based on the dual law of Boolean algebra, which is a reflection of the system safety of the icebreaker assistance operation. When there is no collision risk factor in a minimum cut set, the collision accident does not occur as the top event. Therefore, by obtaining the minimum cut sets, we can know which basic events need RCOs to avoid collision accidents and the number of programs to prevent accidents.

(2) The structural importance degree coefficient of risk factors

The assumption is presented in Section 3.2.1, which makes the probabilities of ship collision risk factors equal. Structural importance degree denotes the importance of each basic event from the structure of fault tree. The structural importance degree of the influence of each collision risk factor on ship collision accidents is analyzed, and they are sorted as shown below. The results are also calculated using Easy Draw. The structural importance degrees of risk factors are shown in Table 3.

Table 3 Structural importance degrees of risk factors

Risk factors	Structural importance degree coefficient
I[[L2-1]]; I[[L2-2]]; I[[L2-3]]; I[[L2-4]]	0.86
I[[L3-2]]; I[[L3-3]]; I[[L2-10]]	0.72
I[[L2-7]]; I[[L4-1]]	0.57
I[[L5-3]]; I[[L2-9]]	0.45
I[[L2-5]]; I[[L2-8]]; I[[L2-6]]	0.42
I[[L5-1]]; I[[L5-2]]; I[[L3-4]]	0.37
I[[L1-4]]; I[[L1-2]]; I[[L3-1]]; I[[L1-3]]; I[[L1-5]]; I[[L1-1]]	0.33

Based on the HFACS-SIBCI model and the proposed FT model, "*Preconditions for unsafe acts*" and "*Unsafe supervision*" have larger structural importance degrees than others, according to Table 2. The results indicate that they have the greatest impact on icebreaker collision accidents. At the same time, the structural importance degrees of *"External factors", "Organizational factors"* and *"Unsafe acts"* are decreasing, which indicates their decreasing effects on icebreaker collision accidents. The results indicate that the environmental factors, such as *Ice conditions [L2-1], Ice ridge [L2-2], Bad visibility [L2-3], Snow or rain weather [L2-4]*, contribute to ship collisions under icebreaker assistance with the structural importance degree coefficient of 0.86, and are followed by *Over safety speed [L3-2], Unmaintained safety distance [L3-3], Improper route selection [L2-10]* with the structural importance degree coefficient of

0.72, and then by *Anti-collision system failure [L2-7]* and *Lack of emergency operations [L4-1]* with the structural importance degree coefficient of 0.57. The structural importance degree coefficients of the above collision risk factors are above 0.5, which indicates that these collision factors have great impact on safe navigation under icebreaker assistance. The structural importance degree coefficients of the other factors are below 0.5, which indicates that these collision factors have lower impact on safe navigation under icebreaker assistance, but they also contribute to ship collisions under icebreaker assistance.

(3) Results verification and RCOs

The analysis of ship collision risk factors under icebreaker assistance is carried out using the HFACS-SIBCI and FTA based on accident reports. The HFACS-SIBCI model for collision accidents between ships and icebreakers is developed for the identification and classification of ship collision risk factors. Then, the FT of ship collision accidents is established according to the statistical analysis of collision risk factors. At the same time, the ship collision risk factors are qualitatively analyzed using the structural importance degree coefficients and the minimum cut sets. Finally, the structural importance degree coefficients of collision risk factors and the statistics of ship collision risk factors under icebreaker assistance mentioned in the accident report are compared, as shown in Figure 7 and Table 3, which indicates that the structural importance degree coefficients are much related to the statistical frequencies of ship collision risk factors. As can be seen from Figure 7, factors, such as *Ice conditions [L2-1], Ice ridge [L2-2], Bad visibility [L2-3], Snow or rain weather [L2-4], Over safety speed [L3-2], Unmaintained safety distance [L3-3]* and *Improper route selection [L2-10]*, have greater impact on safety navigation during icebreaker assistance, which is in good agreement with the result of the qualitative analysis using the FTA. Accordingly, the RCOs are proposed based on the structural importance degree coefficients and the minimum cut sets to provide a theoretical basis for the formulation of risk control strategies. For example, in the first minimum cut set {[L2-9], [L3-4], [L5-1], [L5-2], [L5-3]}, if the icebreaking ability and engine power are very strong, then, as long as the RCOs are adopted to ensure that the icebreaker does not deviate from the suggested route, and there is smooth communication between the ships, a ship collision accident can be effectively avoided. The RCOs are recommended to decrease ship collision risks under Arctic icebreaker assistance.

- Focus on the *preconditions for unsafe acts*. Arctic adverse navigational environment should be avoided, especially areas with severe ice conditions and ice ridges. Constant vigilance is necessary in ice-covered waters due to possible bad visibility during rain, snow, fog etc. The ship crews and the staff of the icebreaker company should keep track of weather forecasts and adverse weather warnings issued by competent authorities to prepare in advance. Another option to avoid adverse navigational environments is to implement routing optimization support tools (Kotovirta et al., 2009; Guinness et al., 2014).

- Focus on the *external factors* and *unsafe supervision*. Ship navigation standards and rules for Arctic ice-covered waters should be abided strictly in order to enhance ship operating proficiency under icebreaker assistance. Moreover, a lookout system should be implemented rigidly, so that the ship can maintain a safety speed of navigation and a safety distance to avoid effectively a collision. The ship officers should observe the navigation speed of the ship and the distance between the two ships in real time by means of radar, GPS and other equipment.
- Focus on *unsafe acts* and *organizational factors*. The icebreaker and the assisted ship should be maintained regularly, focusing on the major safety equipment of the ships. Furthermore, communications and maintenance of the icebreaker and the assisted ship must be enhanced. Once abnormality is found, immediate rectification should be implemented. At the same time, communication equipment should be used correctly in line with the provisions, and equipment should not be idle in a case of need. In addition, effective emergency operations should be developed to reduce collision risks or damages caused by a collision.

According to the Polar Code recommendations and requirements, some general RCOs are given. However, the RCOs proposed in this paper are with more focus on escort operations under icebreaker assistance in ice-covered waters, which can complement the Polar Code for preventing collision accidents.

4. Discussions

In the paper, the HFACS-SIBCI model is established, and the contributing factors of collision accidents are identified and classified. Then, the hierarchical structure model of the ship collision risk factors is presented according to the results of the classification. At the same time, statistical analysis is carried out, which is a basis for the FT modeling using experts' judgment. In addition, the qualitative analysis of ship collision risks is carried out based on the proposed FT model shown in Section 3.2.2, the minimum cut sets of the FT are determined, and the structural importance degree coefficients are calculated based on the minimum cut sets. Finally, the corresponding RCOs are proposed to prevent accident occurrence with the focus on the HFACS-SIBCI model. The results of the research indicate that the most frequent active failure mentioned in the accident reports is *“Preconditions for unsafe acts”*. *"Unsafe acts"* contribute second, followed by *"External factors"*, *"Unsafe supervision"* and *"Organizational factors"* (Figure 7). Regarding the fundamental risk factors based on the FT analysis, the minimum cut sets are listed in Appendix C and can be utilized to prevent ship collision accidents between icebreakers and assisted ships, and the structural importance degrees are calculated in Table 3, which represent the importance degrees of contributing to ship collision accidents. Specifically, the most important active failure in accidents is related to environmental factors, such as *Ice conditions [L2-1], Ice ridge [L2-2], Bad visibility [L2-3],* and *Snow or rain weather [L2-4]*. The second important active failure in accidents is related to supervision, such as *Over safety speed [L3-2], Unmaintained safety distance [L3-3], Improper route selection [L2-10]* etc. The RCOs are described in three aspects according to the results, which can provide theoretical guidance to lawmakers and shipping companies regarding the prevention of ship collision accidents between icebreakers and assisted ships in ice-covered waters.

The proposed approach or model is carried out using the accident reports and expert’s knowledge, which are described in Section 2.3 and Section 3.1.2. The uncertainties on the conclusions will be taken in consider as follow. Inaccuracies in data, assumptions in model and modeling procedures are conditions or choices which may affect the conclusions. Various uncertainty assessment methods have been proposed (Goerlandt and Reniers 2016; Flage and Aven 2009). The simple approach suggested by Flage and Aven (2009) is applied in the research as follow.

The ship collision accident reports contain detailed information including the summary, general description of the assisted ship and icebreaker, external conditions, navigational environment and conclusion of the investigation and so on that occurred in the Baltic Sea, which can facilitate the collision risk factor identification. However, the ship collision accident reports were taken from three different accident investigation boards. Though the number of the ship collision reports is rather small, the qualitative risk identification carried in this research is further complemented with expert knowledge. The uncertainty assessment for ship collision risk factors analysis is shown in Table 4.

Table 4 The uncertainty assessment for ship collision risk factors analysis

Model element	Uncertainty	Justification

Accident reports	Medium	The ship collision accident reports are presented by accident investigation board usually present valuable and detailed information about accidents, which contain the summary, general description of the assisted ship and icebreaker, external conditions, navigational environment and conclusion of the investigation and so on. This allows defining that the uncertainty assessment for accident reports can be considered medium.
Expert knowledge	Medium	The experts have experience to identify and classify the ship collision risk factors under icebreaker assistance. The certainty of the expert's knowledge is medium which will be described regarding the influence of ship collision risk factors identification and classification on the results.
Assumptions	Low	Other factors outside the analysis framework, which could affects the results, e.g. changes in propulsion system, in maneuverability in ice, new navigation systems which may affect the soundness of the analysis. So this allows defining that the uncertainty assessment for accident reports can be considered low.
Models	N/A	No models are used.

In brief, this may question the reliability of the ship collision accident reports when used to determine ship collision risk factors in accident risk modeling. Besides, the research involves uncertainties. The research relies on accident reports formulated in a specific format, where a larger number of accident reports would reduce the uncertainty of the collision risk factors. We will improve the research in the terms of uncertainty analysis in the future. The proposed method of collision risk factors analysis has also some potential benefits to the analysis of collision risks between icebreakers and assisted ships in ice-covered waters.

5. Conclusions

The paper provides comprehensive analysis of ship collision risk factors under icebreaker assistance using the HFACS-SIBCI model and the FTA based on accident reports. First, ship collision risk factors are identified and classified into five levels, including *"Preconditions for unsafe acts", "Unsafe supervision", "External factors", "Organizational factors" and "Unsafe acts"*, where the HFACS-SIBCI model-based hierarchical structure of ship collision risk factors is shown in Table 2 and Figure 6. Second, the FT of ship collisions under icebreaker assistance is constructed using the statistical analysis of the detailed records of the development process of 17 accidents. At the same time, the structural importance degrees of the risk factors are calculated, and the minimum cut sets are listed using the FT qualitative analysis method. Finally, through the qualitative analysis presented in Section 3.2.2, the RCOs are formulated according to the structural importance degree coefficients and the minimum cut sets of collision risk factors based on the HFACS-SIBCI model, which provides theoretical guidance for policy makers and shipping companies regarding the prevention and control of ship collisions under icebreaker assistance. Overall, notwithstanding the assumptions, the comparison of qualitative analysis results and historical accidents shows that the results obtained in this paper are in agreement with the actual situation, and can help to understand ship collision factors during icebreaker assistance. In addition, several advantages of the proposed method for ship collision risk factors analysis are elaborated with the focus on collision risk analysis under icebreaker assistance in ice-covered waters.

Acknowledgment

The authors would like to thank the anonymous reviewers for their constructive suggestions which comprehensively improve the paper. This study was supported by the National Science Foundation of China (NSFC) under Grant No. 51579203 and 51711530033 and the Excellent Dissertation Cultivation Funds of Wuhan University of Technology under Grant No. 2016-YS-041. This work has also been supported by the H2020-MCSA-RISE project "RESET -Reliability and Safety Engineering and Technology for large maritime engineering systems" (No.730888). We thank Professor Jianhua Wu from Wuhan University of Technology, Captain Jianzhong Wang from Polar Research Institute of China and Pilot Hao Wang and Ye Tao from Pilot Station of Tianjin.

Appendix A

- List of the accident analyzed:

#	Icebreaker	The assisted ship	Time	Ice conditions	Power of IB	Type of accident
1	TOR	VINGAVAG	3rd of April 1985 at 23:10 LT	Severe Ice	8.9MW	Collision in ice-covered waters
2	NGORD	SVOLGA	13th of March 1998 at13:40 LT.	Mild Ice	16240 KW	Collision in ice-covered waters
3	YMER	TEQUILA	22th of February 1985 at 04:05 LT.	Severe Ice	16240KW	Collision in ice-covered waters
4	YMER	BREMON	24th of March 1994 at18:10 LT	Rough Ice	16240 KW	Collision in ice-covered waters
5	ALE	SHOUTTLE GOTEBORG	01th of March 1996 at18:20 LT	Normal Ice	3540 KW	Collision in ice-covered waters
6	ALE	ASPEN	14th of February 2011 at13:20 LT	Normal Ice	3540 KW	Collision in ice-covered waters
7	ODEN	GRACHTBORG	27th of January 1999 at 01:55 LT	Rough Ice	18250 KW	Collision in ice-covered waters
8	-	BREMON	27th of February 1994 at 04:38 LT	Normal Ice	18250 KW	Collision in ice-covered waters
9	ODEN	ASSIEUROLINK	11th of March 1994 at19:45 LT	Rough-Very Rough Ice	18250 KW	Collision in ice-covered waters
10	FREJ	SUZAPOLYARNY	1st of February 1987 at 06:10 LT	Normal Ice	16240 KW	Collision in ice-covered waters
11	ATLE	RISOLUTO	7th of March 1993 at 05:41 LT	Fast Pack Ice	16240 KW	Collision in ice-covered waters
12	ATLE	VIOLA GORTHON	10th of February 2003 at 12:25 LT	Rough Refrozen Drift Ice	16240 KW	Collision in ice-covered waters
13	-	ARCTIC	29th of March 1993 at 18:27 LT	Flat Ice	16240 KW	Collision in ice-covered waters
14	-	HALLAREN	22th of March 2001 at 05:20 LT	Normal Ice	16240 KW	Collision in ice-covered waters

15	ATLE	SALSA	20th of January 2011 at 00:57 LT	Mild Ice	16240 KW	Collision in ice-covered waters
16	FREJ	NOREN	1st of April 2006 at 00:57 LT	Rough-Very Rough Ice	16240 KW	Collision in ice-covered waters
17	VAYGACH	NORDIC BARENTS	15st of March 2017 at 16:11 LT	Mild Ice	35.0MW	Collision in ice-covered waters

➢ List of the frequency of contributing factors mentioned:

#	Maneuver failures of the assisted ship	Maneuver failures of the icebreaker	Lack of situational awareness	Negligence	Judgment failures	Ice condition	Ice ridge	Bad visibility	Snow or rain weather	Steering gear failure	Communication equipment failure	Poor communication between ships	Improper route selection	Over safety speed	Unmaintained safety distance	Deviation from suggested route	Lack of emergency operation	Lack of icebreaking ability	Lack of engine power	Anti-collision rule gap
1	1*	0**	1	0	0	0	1	0	0	0	1	0	0	1	1	1	0	0	1	0
2	1	1	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0
3	1	0	1	1	1	1	1	0	0	0	0	1	0	1	1	0	0	0	1	0
4	0	1	1	1	0	0	1	1	1	0	0	0	0	1	0	1	1	1	0	1
5	1	1	0	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	1	0
6	1	1	1	0	0	1	1	1	1	0	0	1	0	1	1	0	1	1	1	0
7	0	0	0	1	0	1	1	1	1	1	0	0	0	1	1	0	0	1	0	0
8	0	1	1	0	0	0	1	0	0	0	0	1	0	1	1	0	0	0	1	0
9	1	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0	1	1	1	0
10	1	0	1	1	1	1	1	0	0	0	0	1	0	1	0	0	0	0	1	0
11	1	0	0	1	0	0	1	1	0	0	0	0	1	1	0	0	1	0	0	0
12	0	1	0	0	0	1	1	0	0	0	0	1	0	0	1	0	1	0	0	0
13	0	0	0	0	0	0	1	1	1	0	0	1	0	1	1	0	0	0	1	0
14	1	1	0	1	0	0	1	1	1	0	0	0	0	1	1	1	1	0	0	0
15	1	1	1	0	0	1	1	1	0	0	0	1	0	1	1	0	0	1	1	0
16	0	1	1	0	0	0	1	0	0	0	1	0	1	1	1	0	0	1	1	0
17	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	1	1	0	1	1
Total	10	11	8	8	3	8	17	7	6	1	2	10	3	15	11	4	8	6	12	2

Note:*1 denotes that the factors are mentioned in the accident;
**0 denotes that the factors are not mentioned in the accident.

Appendix B

➢ Format of the questionnaire provided to identify and classify the ship collision risk factors:

ship collision risk factors	Unsafe acts	Preconditions for unsafe acts	Unsafe supervision	Organizational factors	External factors
Maneuver failures of the assisted ship	√				
Maneuver failures of the icebreaker	√				
……	……	……	……	……	……
What else do you think?					
Engine failure		√			
……	……	……	……	……	……

Appendix C

➢ 29 minimum cut sets are shown as follow:

Minimum cut sets of the FT for collision accidents under icebreaker assistance

{[L3-2],[L3-4],[L5-1],[L5-2]}； {[L1-1],[L1-3],[L1-5],[L2-8]}； {[L1-1],[L1-3],[L1-5],[L2-6]}；{[L2-5],[L2-7],[L4-1]}； {[L1-2],[L1-4],[L2-5],[L3-1]}； {[L2-7],[L2-8],[L4-1]}； {[L1-2],[L1-4],[L2-8],[L3-1]}； {[L2-6],[L2-7],[L4-1]}； {[L1-2],[L1-4],[L2-6],[L3-1]}； {[L2-1],[L2-3],[L2-9],[L5-3]}； {[L2-1],[L2-3],[L2-10]}； {[L2-1],[L2-3],[L3-2]}； {[L2-2],[L2-3],[L2-9],[L5-3]}； {[L2-2],[L2-3],[L2-10]}； {[L2-2],[L2-3],[L3-2]}； {[L2-1],[L2-4],[L2-9],[L5-3]}； {[L2-1],[L2-4],[L2-10]}； {[L2-1],[L2-4],[L3-2]}； {[L2-2],[L2-4],[L2-9],[L5-3]}； {[L2-2],[L2-4],[L2-10]}； {[L2-2],[L2-4],[L3-2]}； {[L3-3],[L3-4],[L5-1],[L5-2]}； {[L2-1],[L2-3],[L3-3]}； {[L2-2],[L2-3],[L3-3]}； {[L2-1],[L2-4],[L3-3]}； {[L2-2],[L2-4],[L3-3]}；{[L2-9],[L3-4],[L5-1],[L5-2],[L5-3]}； {[L1-1],[L1-3],[L1-5],[L2-5]}； {[L3-4],[L5-1],[L5-2],[L2-10]}；
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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