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A root cause analysis for Arctic Marine accidents from 1993 to 2011

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ABSTRACT

The aim of this paper is to investigate the marine accidents/incidents which are recorded by Marine Accident Investigation Branch (MAIB) as occurring north of 66°33′ in the years from 1993 to 2011 to reveal their causes by using root cause analysis. Due to the global warming, increase of ice melt in North Pole is expected in the future. In the further years, number of vessels and shipping traffic will dramatically increase in the Arctic region. Thus, navigation will become more difficult in the Arctic Region. Consequently, to guide the vessels navigating in this region, an analysis of the previous marine accidents/incidents occurring in the Arctic region is required to improve the safety. Therefore, Root Cause Analysis (RCA) is proposed to clarify the causes and prevent the future incidents from happening. As an empirical study, fault trees of collision and grounding for the Arctic Region is constructed. Fuzzy Fault Tree Analysis (FFTA) is applied to this problem in order to propose a recommendation to reduce the occurrence probabilities. Risk levels of each factors are determined by expert consultations. In this study, Accident to Person is found as the most observed incident. Negligence/careless of injured person has the highest priority for root causes of marine accidents. In order to combat this phenomenon, scientific results of this study can open up a dialog between law makers and shipping companies those aim to decline incidents. Furthermore, it is assumed to contribute representatives developing crew training manuals and competence requirements as well as opening Arctic navigation training centers.

1. Introduction

After considering the requirements for safety of vessels operating in the ice covered waters, International Maritime Organization (IMO) identified and published an international code named Polar Code (Jensen, 2007). Polar Code is culminated in the process of previous IMO documents (IMO Documents, 2014) and voluntary guidelines (IMO, 2010). Polar Code covers the subjects of the design, construction, equipment, operational, training and search and rescue.

International Convention for the Safety of Life at Sea (SOLAS) is another significant regulation to make shipping safer. The subcommittee on ship design and construction (SDC) has agreed to make the safety measures mandatory for ships operating in polar waters. The environmental protections are considered by the International Convention for the Prevention of Pollution from Ships (MARPOL, 1978) United Nations Convention on the Law of the Sea (UNCLOS) entered into force in 1994, signed by 162 countries. UNCLOS is a legal framework deals with the rights and responsibilities of governments in their use of ocean space.

There are many safety procedures on environmental security in the Arctic Ocean (Berkman and Vylegzhanin, 2013; Deggim, 2009; Young, 1995). These studies emphasize the personal, technical and navigational requirements for ships operating in polar waters.

STCW requirements stress the competency of masters and officers of ships operating in polar waters (STCW, 1995). Also, it mentions the performance of a ship, importance of training, voyage and passage planning for a ship in ice, local requirements for entrance to the foreign. However, training guidance for personnel on ships operating in ice-covered waters should be determined by considering the information of the root causes of the marine accidents occurring in the Arctic region.

Poor weather conditions, cold temperature, charting, lack of communication and navigational aids, remoteness are some of the challenges for the mariners in the Arctic region. Besides, operating in polar regions has a high risk, forecasts demonstrate that the Arctic shipping in volume is at an increasing trend. Therefore, these challenges need to be rooted for both safety of life and sustainability of the Arctic navigation.

In this study, the data of available marine accidents occurring in the Arctic region are analyzed. Then, the root causes of all incidents

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are determined in a systematic approach. Then, a fuzzy fault tree analysis model is presented for the marine accidents occurred in the Arctic region. As an empirical study, collision and grounding are considered. Other incidents such as direct damage of ice to the vessel, hazards of icing, stuck in ice or fire and explosion are left for future study. It is believed that this analysis will contribute to the ice navigation in the Arctic region for taking precautions and future studies for new regulations.

2. Literature review

There exist a vast amount of literature on various aspects of navigation in the Arctic region. A comprehensive review of previous research on this topic within Arctic shipping can be found in Schøyen and Bråthen (2011), Ho (2010), Verny and Grigentin (2009). Economic aspects of Arctic transportation as well as its increase over the past decade were discussed in Lasserre (2014) and Hong (2012). These studies considered both Arctic routes and profitability. Existing navigation-oriented research on the Arctic region can broadly categorized into four groups: (1) Arctic shipping routes and profitability (2) environmental impacts and studies on Arctic meteorology and (3) Arctic politics (4) navigation. Previous research in these categories is briefly described below.

The problem of economic viability of using the Northen Sea Route was studied in Granberg (1998), Liu and Kronbak (2010) and Harsem et al. (2011). The same problem was considered in Somanathan et al. (2009) under simulating the Northwest Passage by comparing the alternative routes in terms of predefined constraints, whereas Lasserre and Pelletier (2011) presents interest of shipping companies in developing activities in the Arctic.

An overview of Arctic sea ice in global atmospheric circulation can be found in Budikova (2009). History of sea ice in the Arctic is given in Kellogg (1995) and Polyak et al. (2010). A comparison of the past rates of climate changes in the Arctic region was given in White and Alley (2010), glacial history of Arctic was studied in Jakobsson et al. (2014a). Yamanouchi (2011) proposed some explanations on early 20th century warming in the Arctic whereas Jakobsson et al. (2014b) introduced a program to review the Arctic quaternary environmental change (Yamanouchi, 2011; Jakobsson et al., 2014b). Models for snow depth and sea ice extent in the Arctic were proposed in Park et al. (2013). Ford et al. (2006) and Doel et al. (2014) investigated vulnerability to climate change in the Arctic.

Studies of Arctic policy on the European Union is overviewed in Wegge (2011) and Offerdal (2010,). For the USA politics, National strategy for the Arctic region (2013) is declared. Blank (2011) and Padrtová (2012) conducted strategic studies regarding to Russian politics. XJensen and Skedsmo (2010) compares the Norwegian and Russian policies by using the discourse analysis. Moreover, legal perspectives for the Arctic is studied in Stokke (2007).

Regarding the icebreaking service, Parsons et al. (2011) discussed the operational infrastructure and effectiveness of the icebreakers in the Arctic region. Kotovirta and Jalonen (2009) studied route optimization ice covered waters. For optimal ship navigation, impacts of turn-radius constraints and safety distance were studied in Ari et al. (2013). On the other hand, Snider (2012) and Buysse (2007) describe challenges of polar ship operations and handling ships in ice. Satellite measurements and remote sensing technology regarding the both sea ice detection and ice navigation are studied in Parkinson and Cavalieri (2008) and Alexandrov et al. (2010).

Root Cause Analysis (RCA) is a combined approach which represents the methodologies and tools for investigating the adverse incidents, causalities and tragic events (Carroll, 1998). It is developed for the analysis of industrial incidents and used for several fields such as food safety management, quality assurance, medicine, health-care systems for disease detection, software engineering, and clinical investigations, etc. (Andersen and Fagerhaug, 2006). RCA stands on the assumption that threats and solutions to human lives, properties and environment, which can solely be identified through accurate and analytic processes. The aim of RCA is to determine the causal chain and sooner the root cause factors that are based on active or individual errors (Reason, 1990). Therefore, it focuses on the significance of unbiased examination, investigation and criticism (Shojania et al., 2001). RCA is a process conducted by a systematic reporting of adverse events, their layers to determine the relative priority, investigation and production of recommendations to promote safety. Amo (1997) describes the steps of RCA (1) identification of the problem; (2) study the accident; (3) collect the data; (4) determine the causes; (5) chart out the general frame; and (6) discuss the results. Bagian et al. (2002) and Vincent et al. (1999) have put the diverse variations on this step-wise and systematic method. It should be mentioned that RCA is not fully consistent. Time constraints, lack of expertise and experience are reported as some limitations by Braithwaite et al. (2006). Similarly, Tamuz et al. (2011) expresses the weaknesses of the avoidance to the influence of organizational politics on decision making during the RCA process.

Marine casualties in the open seas and conventional maritime accident analyses have widely been studied by many scholars. For instance, Ellis (2011) focuses on the marine accidents during the transport of packaged dangerous goods. Antão et al. (2008) define the causes of occupational accidents in the fishing sector in Portugal. Psarros et al. (2010) point out the analysis of tanker casualty records. Human and organizational factor analysis for marine casualties has been studied by Chen et al. (2013). Also, several non-profit organizations (Appendix A) analyze the marine accidents. In this study, RCA is used for marine accidents which is

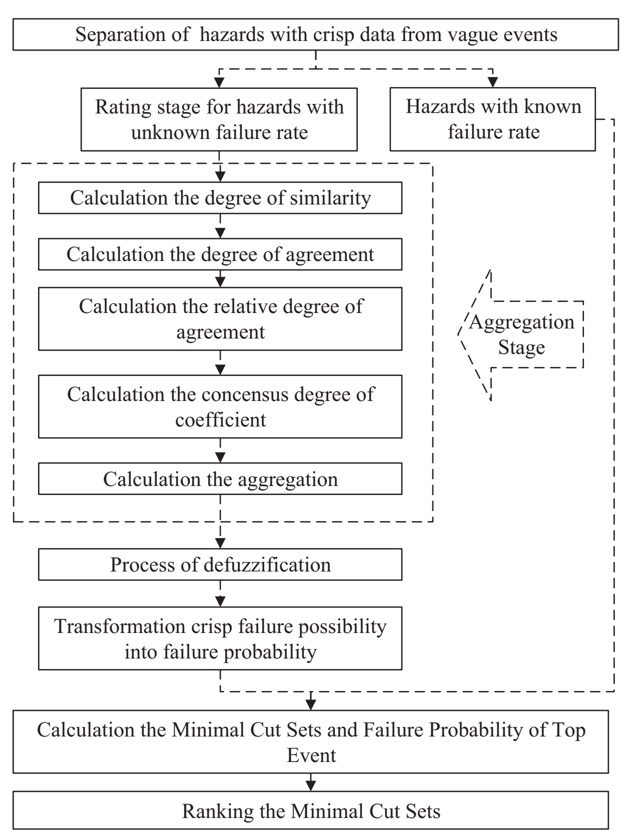

Fig. 1. Structure of the FFTA methodology.

occurring in the Arctic region. To our knowledge, root cause analysis for Arctic Marine accidents has not yet been implemented.

Risk analysis of the marine accidents are highly studied in the literature. For instance, Ercan et al. (1998) studied risk assessment of fishing vessels by using fault tree analysis and Uğurlu et al. (2013) has conducted the same method in oil tanker accidents. However, the work of Jalonen et al. (2005) seems to be the only study in the literature that considers the risk analysis of the ice navigation in the Baltic Sea from a navigator's point of view.

3. Materials and methods

3.1. Data collection

This study involves the review of the literature and available data gathered from the databases which are given in Appendix A. MAIB is the main research reference for the root cause analysis. Moreover, after gathering the data from Arctic-related non-profit organizations (i.e. AMSA (Arctic Council, 2013)), expert consultations are conducted for the basic events of each cases.

3.2. Root Cause Analysis (RCA)

RCA is a combined and flexible analytic problem solving method, which identifies the deep factors of faults, failures and problems (Rooney and Heuvel, 2004). Therefore, there are diverse approaches, graphs and mentality for implementing the RCA. The purpose of this method is to prevent the similar undesirable outcomes of recurrence. RCA as an effective technique, which is an iterative and retrospective process; thus, it is open for a continuous improvement. Also being a reactive and preemptive method, it is used to predict the probable events (Ammerman, 1998). For marine accidents, failure based-RCA is rooted. For an effective root cause analysis, investigation is performed in a systematic manner considering there may be several roots for a basic event. Therefore, the sequence of events is required to establish the relationship between the events, definition and prevention of the problem. The development process of the RCA includes not only data collection and identification of root problems, but it allows cause charting, recommendation for the consequences, generating and performing (Heuvel, 2005).

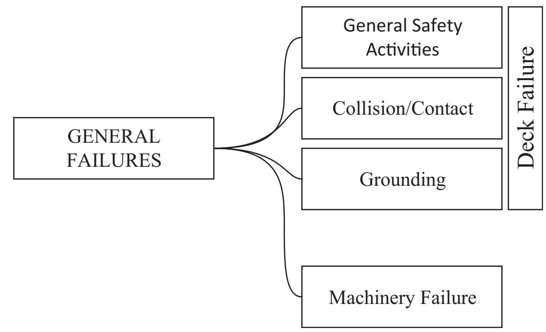

Fig. 3. Current reality tree for general failures observed in the arctic region.

Steps of root cause analysis:

Step 1. Definition of the problem and description of the intended events.
Step 2. Data gatherings and classification of events.
Step 3. Identification of the causes.
Step 4. Classification of the events in the sequence.
Step 5. Construction of the general diagram.
Step 6. Identifying of corrective actions for each basic event.
Step 7. Implementing the rearranged root causes.
Step 8. Test the efficiency of the final diagram.
Step 9. Identification of usage of other methodologies for the problem solution.
Step 10. Improvement of the system by the other instances of the event.

3.3. Current Reality Tree (CRT)

CRT is an appropriate root cause analysis tool to handle the problems which are interdependent (Doggett, 2005). Two entities are connected to each other with the if-then statement. The CRT is constructed as follows: (i) The problems are listed and related to the undesired event. (ii) Test each undesired event. (iii) Determine of the causes and effects. (iv) Test the relationship by using the rules for the evaluation of assumptions and logic. (v) Connection process of undesired events is completed by using

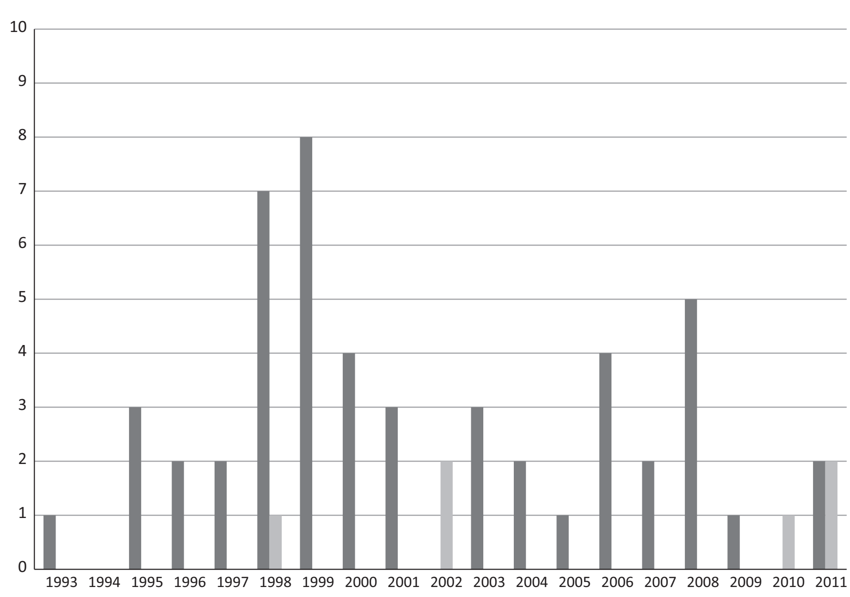

Fig. 2. Number of deaths and injured people.

Table 1
Distribution of vessel types to the countries.

Vessel types	Denmark	Canada	Russian federation	Greenland	Iceland	USA	Norway
Container	8	–	2	5	19	–	–
Tug/Barge	–	10	–	–	3	9	–
Bulk carrier	5	15	23	6	2	14	68
General Cargo	83	9	14	11	74	–	28
Passenger	33	6		36	41	2	46
Tanker	10	7	12	5	29	1	12
Government	–	12	7	16	28	16	–
Fishing	2	27	–	–	152	335	–
Oil/Gas service	–	2	–	1	–	–	–
Pleasure Craft	–	1	–	1	3	–	–
Research	–	–	–	–	–	–	3
Total	141	89	58	81	351	377	157

Table 2
Accident types.

Contributor to accidents	Number of accidents	Percentage
Accident to person	50	76.92
Collisions and contacts	4	6.15
Grounding	4	6.15
Machinery failure	3	4.62
Flooding and foundering	2	3.08
Fires and explosions	2	3.08
Capsizing and listing	0	0.00
Total	65	100

if-then logic. (vi) Logical relationship is then constructed. The relationship between the events were linked by the authors, based on the MAIB's report.

3.4. Fuzzy Fault Tree Analysis (FFTA)

FTA is a systematic approach to estimate the safety and reliability of complex systems both in qualitative and quantitative manner (Wang et al., 2013). The FFTA has very extensive usage area in many fields, such as safety assessment (2014) risk analysis (2014), chemical (2014), nuclear power (2014) and etc. (Aiyou

Table 3
Number of incidents, deaths and injuries for the vessel types for 19-year period.

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Number of Incidents																			
Fish Catching, Processing/Trawlers	1		1	3	1	5	7	2			1	1		4	1	3			
Passenger/Cruise Ship					1	2	1	3	4		2	1	1	2	1	2	1		2
Passenger Ro-Ro Vehicle/Passenger Ferry								1											
Survey/Research						1													2
Port Service/Tug							1												
Commercial/Offshore Supply						1												1	
Commercial/Drilling						1												1	
Commercial/Naval support, RFA										1									
Dry Cargo Reefer													1						
Small Sail Training Vessels										1									
Non-Commercial/Pleasure craft								1											
Tanker/combination carrier														1					
Number of Deaths																			
Fish Catching, Processing/Trawlers						1													
Passenger/Cruise Ship																			1
Passenger Ro-Ro Vehicle/Passenger Ferry																			
Survey/Research																			1
Port Service/Tug																			
Commercial/Offshore Supply																		1	
Commercial/Drilling																			
Commercial/Naval support, RFA										1									
Dry Cargo Reefer																			
Small Sail Training Vessels										1									
Non-Commercial/Pleasure craft																			
Tanker/combination carrier																			
Number of Injuries																			
Fish Catching, Processing/Trawlers	1		3	2	1	3	6	1			1	1		3	1	4			
Passenger/Cruise Ship					1	2	1	3	3		2	1	1	1	1	1	1		1
Passenger Ro-Ro Vehicle/Passenger Ferry																			
Survey/Research																			1
Port Service/Tug							1												
Commercial/Offshore Supply						1													
Commercial/Drilling						1													
Commercial/Naval support, RFA																			
Dry Cargo Reefer																			
Small Sail Training Vessels																			
Non-Commercial/Pleasure craft								*											
Tanker/combination carrier																			

Table 4
Root causes of the marine accidents.

Contributor to accidents	Time Occurrence
Negligence/carelessness of injured person	13
Personnel unfamiliar with equipment/not trained in use	6
Inattention	2
Perception Abilities	1
Situational Awareness or Communication Inadequate	3
Design Inadequate	1
Heavy Weather	2
Alcohol/Drugs Use	2
Illness	1
Perception of Risk	3
Violation of procedures	1
Visual Environment-Darkness	1
Stumbling/tripping over fixed door sill, step, obstruction	7
Vessel movement weather conditions	6
Procedures Inadequate	2
Lack of communication or coordination	2
Vigilance	1
Improper or inadequate footwear/clothing/PPE	2
Lifting/carrying – poor manual handling	6
Poor/slippery/uneven surface	3
Wave washing inboard	2
Hit by swinging load/falling gear	2
Involving portable tools/equipment/machinery	2
Exposure to dangerous atmosphere or substance	1
Fire/Explosion	1
Auxiliary machinery	1
Material/mechanical defect	5
Bridge Procedures	4
Maneuverability	1
Navigation/Communication -Equipment	4
Navigational Instruments (Radar, GPS, ECDIS, etc.)	3
Inadequate Passage Planning/Track Monitoring	2
Fatigue	1
Poor Decision Making	1
Task difficulty	1
Equipment not available	1
Visibility	1
Flooding/Foundering	1
Company standing orders inadequate, insufficient, conflicting	1
Publications/plans not up to date	1
Safety management system failure	2
Procedures inadequate	1
Competence	1
Wire/rope/net jamming, jumping slipping or coming off sheave	2
Other factors	2
Total	109

et al., 2014; Rajakarunakaran et al., 2015; Purba, 2014; Shi et al., 2014). Detailed studies are performed by using fuzzy set theory in FTA. The pioneer research on this field is performed by Tanaka et al. (1983a). In that study, the probabilities of BEs are expressed as trapezoidal fuzzy numbers and applied the fuzzy extension principle to determine the probability of BEs. The further researches are studied by Misra and Weber (1990). An evaluation system is proposed based on possibility distribution related with BEs and a fuzzy algebra is used to combine them. Then, Singer (1990) analysed fuzzy reliability by applying L–R (left–right) fuzzy numbers (Singer, 1990). Accordingly, Cheng and Mon (1993) proposed a method by taking into consideration the failure probabilities of BEs, based on triangular fuzzy numbers.

Lin and Wang (2013) proposed a method based on FFTA, which can measure the failure probability and possibility simultaneously (Wang et al., 2013). Moreover, Kai-Yuan et al. (1991) and Huang et al. (2004) adopted a theory based on possibility theory in order to analyze the FTA structure. The studies of He et al. (2007) can deal with the some obstructions of conventional FTA by using possibilistic measures and fuzzy logic. Moreover, Tanaka et al. (1983b) proposed an improvement index to evaluate the importance of BEs. Furuta and Shiraishi (1984) developed a group of value which represent the fuzzy membership functions to determine the importance of BEs (Furuta and Shiraishi, 1984). As seen above, the FFTA has very extensive usage area in many engineering fields for years.

Table 5
Criteria for determining the expert weights.

Parameters	Classification	Score
Professional position	Academician	5
	Company operations manager	4
	Company deck inspector	3
	Master	2
	Chief officer	1
Sea service time (year)	16	5
	11–15	4
	6–10	3
	3–5	2
	2	1
Shore service time (year)	26	5
	16–25	4
	11–15	3
	6–10	2
	5	1
Educational level	PhD	5
	Master	4
	Bachelor	3
	HND	2
	School Level	1

For the risk related research, expert consultations should be carried out since the situations have insufficient or no data. A framework based on fuzzy set theory and FTA is aimed for the experts who express their opinions qualitative manner. This framework is capable for assessment of the judgments. The model is shown on Fig. 1 (Lavasani et al., 2011). Firstly, root causes in other words basic events (BEs) are separated as fault rate is known and fault rate is unknown. At the second phase, the probability of known BEs fault rates are obtained. Third phase, expert consultation is conducted for the probability of unknown BEs. Then judgment values are assigned to the each unknown BEs. This evaluation is generally as fuzzy number format. Fourth step is an aggregation procedure. For all vague BEs, this phase is completed by aggregating of expert opinions which are expressed in a linguistic manner. After an appropriate algorithm application, the fuzzification process is handled by the conversion of fuzzy possibilities of expert judgments into crisp expressions. At the sixth phase, crisp possibilities are converted as fault probabilities. Then minimal cut sets (MCSs) and TE estimations are ended. Lastly, MCSs are ranged.

As mentioned in the first phase of the methodology, separation process is operated for the BEs which have known fault rates and BEs which have unknown fault rates. Some fault probabilities are given in these sources. Thus, BEs which have known fault rates and BEs which have unknown fault rates are required to be separated. However, for collision and grounding in the Arctic region, there exists no known data regarding the BEs.

4. Accident data

The data below represents 65 reported accidents/incidents of marine causalities in the Arctic Region over a time span of 18 years. Fig. 2 shows the total number of deaths and injured people (see Fig. 3).

Fig. 2 includes all types of vessels that navigated in the Arctic Region. Since regular transportation through the Arctic region started in summer 2009, from this graph, it is evident that deaths and injuries may inevitably continue to occur in future years. From 1994 onwards, it is clear that there was a sharp increase in the number of injuries.

Based on the (2009) Arctic Marine Shipping Assessment Report, Arctic Council, there are approximately 1254 registered vessels in the Arctic region. The distribution of the vessel types to the countries are given in Table 1.

69 vessels involved these accidents and incidents were reported to the MAIB; *Accident to Person* is noted as the main contributor to the number of incidents. The data of the marine accident analysis show that *Accident to Person* has contributed to 76.92% of all accidents. This is attributed to several factors including inattention, heavy weather, age, lack of communication and etc. The next highest contributors to accidents are found to be collisions/contacts and grounding. A comparison of all accident types is made as seen in Table 2.

The marine incidents that occurred in the Arctic region reflect the severity of the accidents as well as the number of deaths and injuries which are gathered and presented in Table 3.

5. Accident analysis

Risk assessment plays a significant role to mitigate the marine incidents occurring above 66°33′. The number of the vessels navigating in the Arctic region has increased in the last five years. Thus, concerns have increased if similar incidents may not be prevented in the future. From the literature, risk analysis of Arctic region has been limited to its poor weather conditions, remoteness and knowledge of ice detection. In the literature, very little work has been carried out in the literature that accounts for the operational and navigational marine accident analysis occurring above 66°33′. In order to demonstrate significance of the safety assessment on vessels operating in the Arctic region, root causes of each accident type are classified and summarized below.

Table 4 indicates the root causes of the marine incidents that occurred in the Arctic region (see Table 5).

50 of 65 official accident reports indicate that *Accident to Person* has a highest priority relates to the official marine accident data based on the incidents recorded by MAIB as occurring north of 66°33′. The location of the 36 incidents occurred in the high seas, 7 occurred in the coastal waters and 7 incidents occurred in the near port and harbor areas. The number of the cruise ships is 21; fish catching/processing vessels is 24 and other commercial vessels associated with offshore industry, naval support, port service and commercial sailing vessel is 5. The total number of the sea state during each *Accident to Person* incidents is 32 and interestingly 16 of 32 incidents occurred in a calm sea state that is less than 2 ft., 9 of 32 are moderate, 3 are sheltered waters and only 4 are

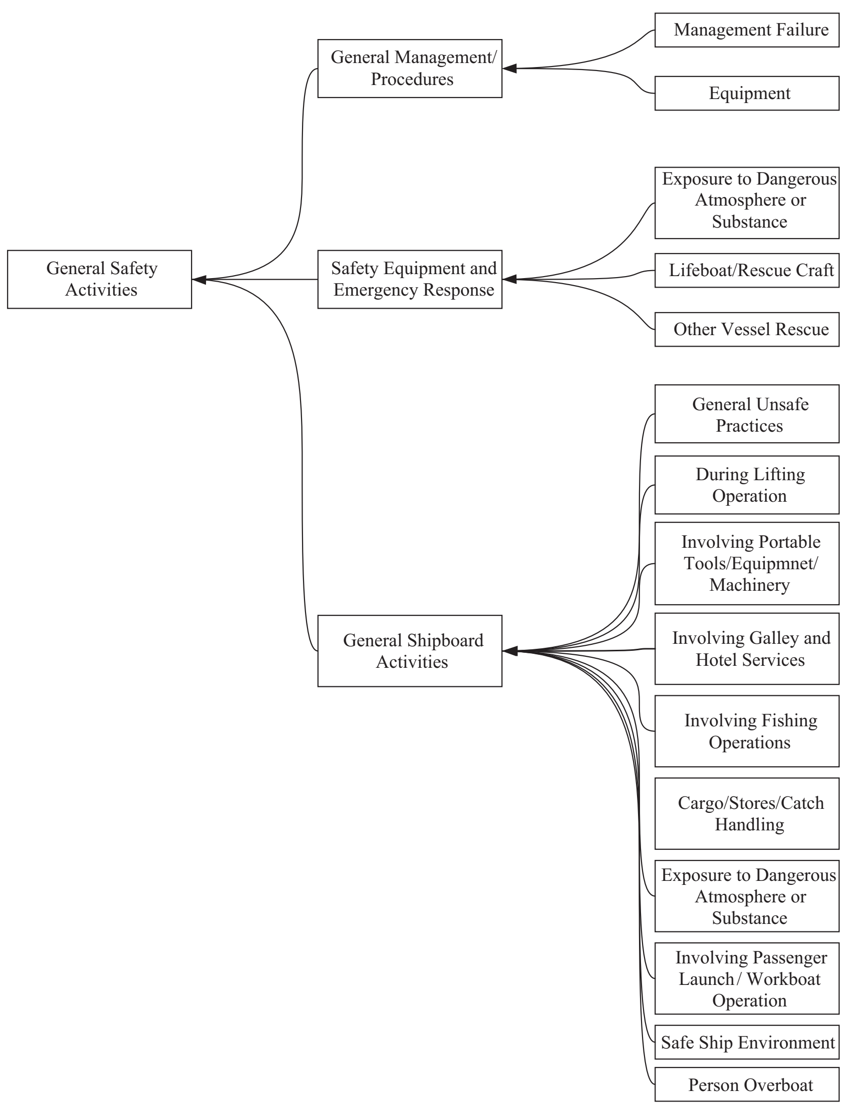

Fig. 4. Current reality tree for the root causes of failures related to general safety activities.

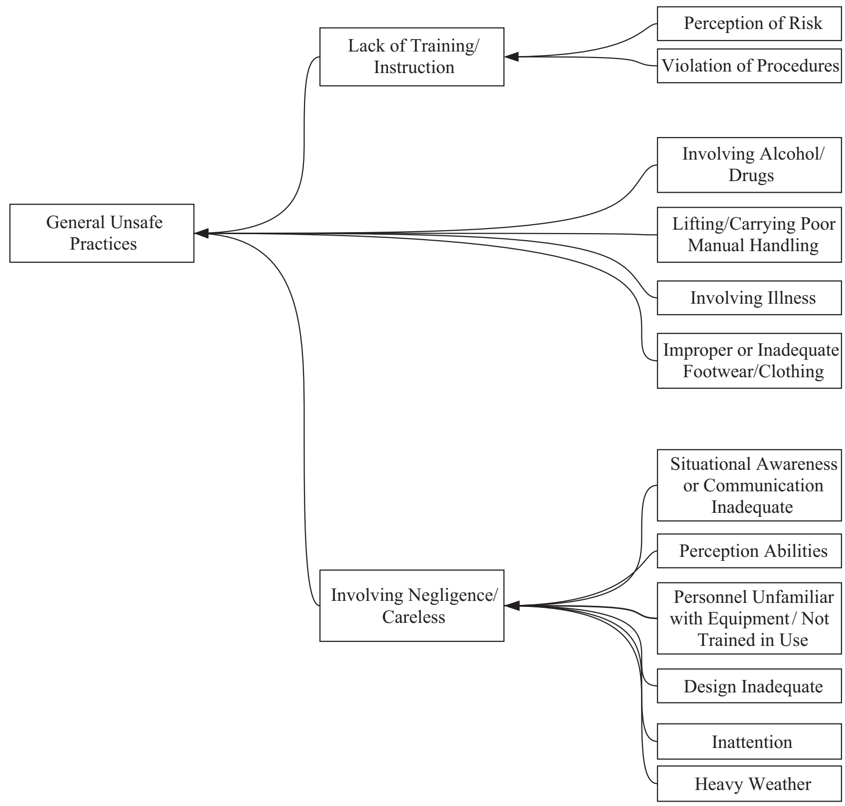

Fig. 5. Current reality tree which identifies the root causes of general unsafe practices.

rough sea state. According to the data, the total number of natural light during the incidents is 28 of 44 light, 16 of 44 is both semi-dark and dark.

Failure of a single maritime incident might depend on several factors. *General Failures* might be depicted as seen in Fig. 4. *General safety activities*, *Collision/Contact* and *Grounding* are observed as deck failures. *Machinery Failure* is rooted separately. Marine accidents might occur during the *General Safety Activities* which crew/person directly involved in. It is categorized into three groups: *General Management/Procedures*, *Safety Equipment and Emergency Response* and *General Shipboard Activities*. Then, the items given on the Current Reality Tree are rooted.

General Unsafe Practices are directly related to the personnel discipline and alertness. The failures cause from the lack of training/instruction and negligence/careless. In marine accidents, more than one cause may be applicable to a particular accident. As seen on Fig. 5, root causes of the *General Unsafe Practices* related to the human factor are personnel unfamiliarity with equipment/not

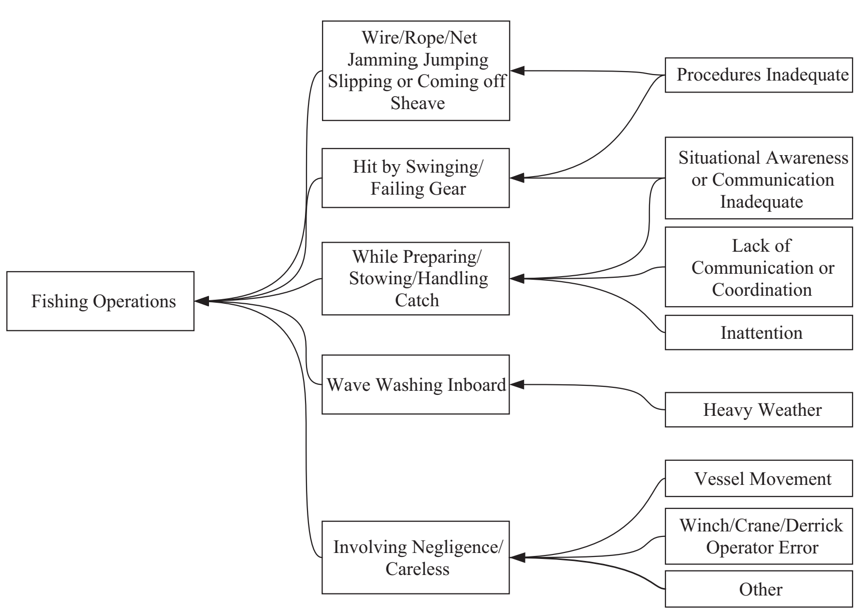

Fig. 6. Current reality tree for the root causes of failures related to fishing operations.

trained in use, inattention, perception abilities, situational awareness or communication inadequacy, alcohol use, perception of risk, violation of procedures.

Design inadequacy and heavy weather are the root causes of the technical causes. Total number of marine incidents involving the technical factor is only 2. Rest of the causes are directly related to the human factor which are 27. Root causes of the failures during the fishing activities is given on Fig. 6.

Due to their complicated and complex structures, applications of in-depth analysis are hard for all of the marine incidents. However, some examples regarding to human factor might be given. For instance, a summary of an incident reports that a relief master held a Dynamic Positioning (DP) endorsement but was not familiar with the particular DP model fitted to the platform supply ship. It is intended to carry out a type specific familiarization training before a master takes command of the particular vessel. In addition, the company are investigating all senior staff who use the DP system to ensure they are correctly trained and, if not, training will be provided. Second example, a female passenger was walking on an open deck of a 294 m. long cruise ship, at anchor in fair weather, when she tripped over a sun lounger, she fell on her left side. She attended the on board medical center, where she was diagnosed as having fractured her left hip. The passenger was carrying a tray and food when she fell and was suspected by the on-board doctor to have been under the influence of alcohol, which was substantiated by the passenger's account. The area of deck where the sun lounger was found to be dry and free of obstructions, and the accident appears to be attributable to the passenger not paying attention whilst carrying the tray, possibly affected by the influence of alcohol. Visual environment, vessel movement/weather conditions and perception of risk are the root causes of the problems occurred in the Arctic region. Darkness, large waves, lurching, replacement of the properties due to rough weather conditions are some causes related to safe ship environment (Fig. 7).

According to MAIB's report, there are three collisions and one contact occurred in the Arctic Circle. A case of collision is summarized as; two fishing vessels collided in fog. While one was preparing to shoot, the other was in the process of shooting. There is conflicting evidence as to whether or not one of the vessels started to shoot and crossed the bows of the other in close proximity so that other vessel was unable to take effective avoiding action. Another case is given as; while one is struck the smaller vessel, which was at anchor. Then, smaller one sank very quickly. The skipper only crew member on-board was picked up by the other vessel uninjured. Skipper of the smaller vessel sounded air horn to warn the other vessel and attempted to throw off anchor rope. The cause is due to poor watch-keeping by the bigger vessel's watch-keeper. The majority of the collisions occur in a calm sea state with a good visibility (5–10 nautical miles). However, the consequences of the accidents are minor and material damage. Grounding incidents are associated with passenger cruise ship, reefer and trawlers. Poor decision-making and bridge procedures are common causes (Fig. 8). However, many cases involve navigational error. Due to the vessel turning either later or more slowly than planned, the absence of a suitable large scale chart, speed-too fast for conditions and darkness are the other contributory factors.

Gear box, winch and propeller damages are the main machinery damages. Although machinery damages do not directly threaten the vessel or lives, other factors such as cold weather conditions or being stuck in a ice field, the consequences could be dangerous (Fig. 9). Therefore, propeller, shaft and gear arrangement should be determined based on the rules of the ice classification society.

The two foundering/flooding cases can be summarized as follows: (1) 68 meter survey vessel was in heavy weather. Seas on beam passed down ventilator into engine room and entered the main switchboard. All power was lost. Temporary repairs allowed vessel to reach port. (2) Flooding caused by rudder gland packing

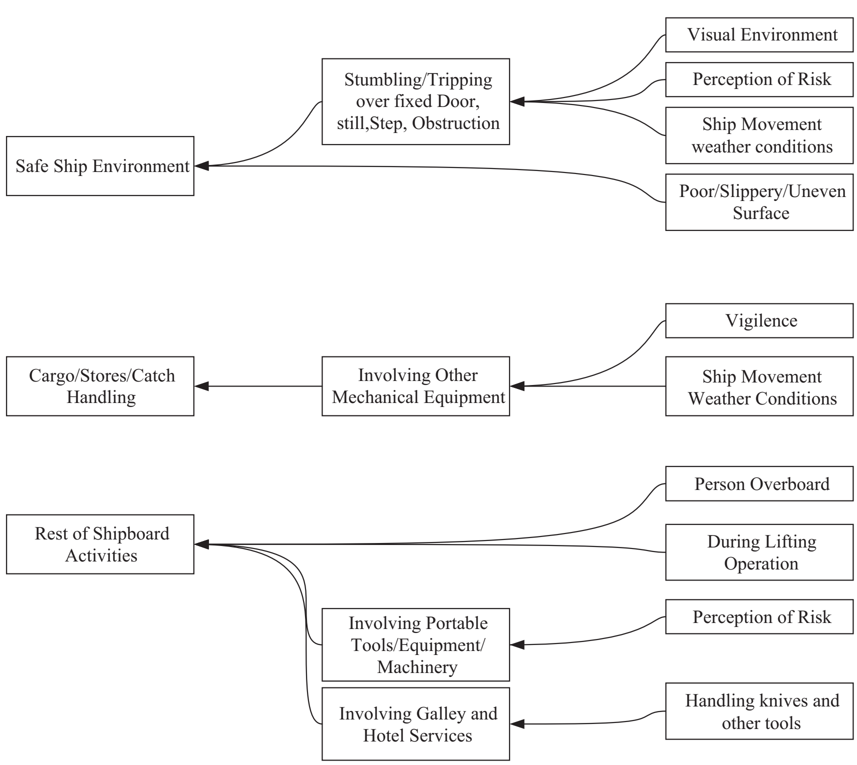

Fig. 7. Current reality tree for the root causes of failures related to safe ship environment, cargo/stores/catch handling and rest of ship activities.

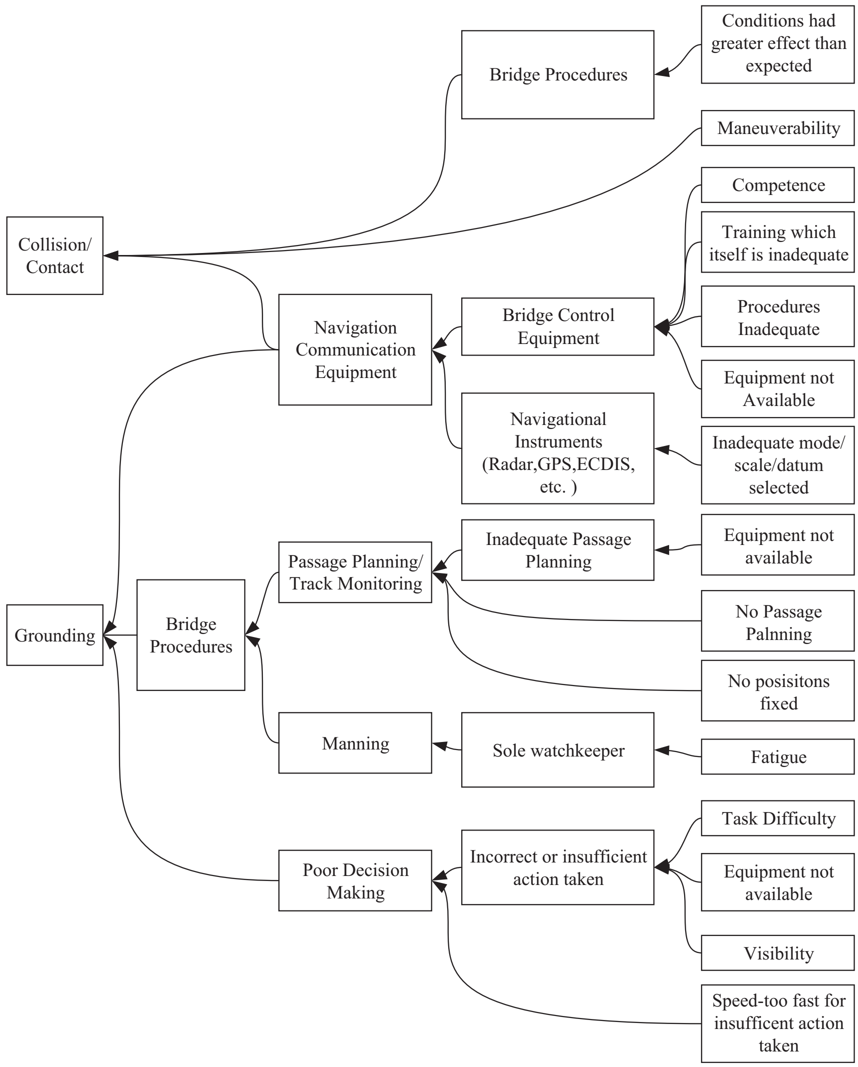

Fig. 8. Current reality tree for the root causes of grounding and collision/contact.

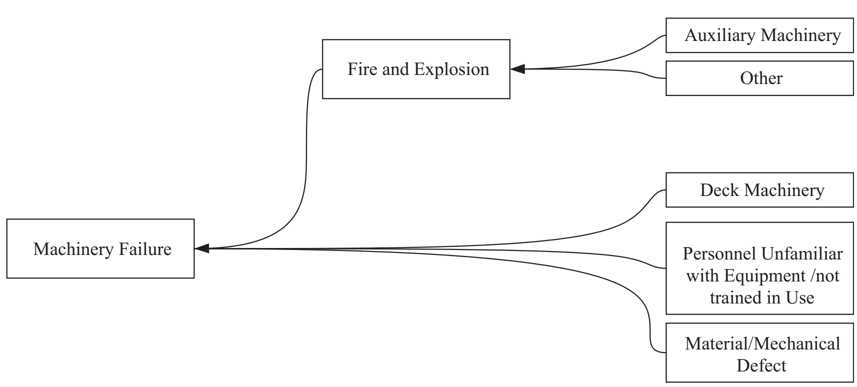

Fig. 9. Current reality tree for the root causes of machinery failure.

failure. Only noticed when hold was put onto the rudder. Fires and explosions were found on the sludge incinerator and galley. The reasons are detected as incorrect replacements and wrong fittings.

6. Empirical study

Although the analyses of different fault trees are similar, due to its nature, everyone can generate different fault trees based on their perspectives to the subject. In this study, in order to open a corridor for computing the root causes and occurrence probabilities of TEs, collision (Fig. 11) and grounding (Fig. 10) are preferred to construct. MAIB report declares 4 collisions and contacts however, according to AMSA report, it mentions the total number of 22 collision and 68 grounding in the Arctic between the years 1995 and 2004 (Arctic Council, 2013). The total number of each type of accidents are not clear in the literature.

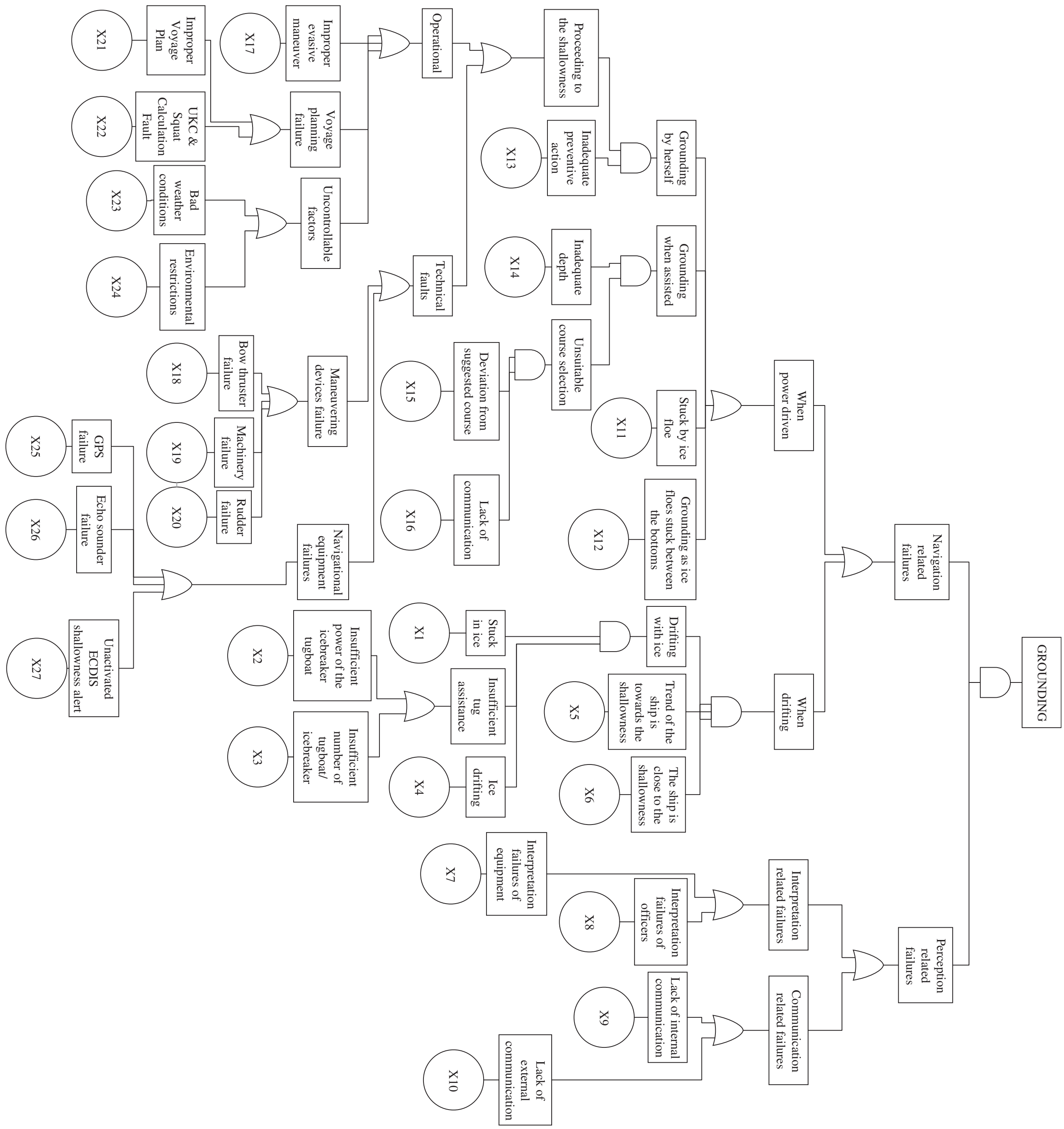

Fig. 10. Fault tree of grounding.

Furthermore, root causes may vary because of the unstable nature of accidents. Moreover, relevant data belong to different time intervals. For example, since MAIB report covers 1993–2011, AMSA report covers 1995–2004. Since MAIB report explains the events in detail, AMSA report provides the only numbers of accidents. The total number of incidents mentioned in the AMSA report is more than mentioned in the MAIB report. Besides MAIB report, academicians, masters and chief officers are asked root causes in order to generate the fault trees. Due to Arctic shipping is a new concept, there are very limited data to determine the probability of each BE. Therefore, we ignored the stages of hazard separation and calculation with failure rate. To overcome this, expert consultation is conducted.

6.1. Rating scale

Chen and Hwang (1992) have developed an appropriate numerical approximation method which transforms the linguistic expressions into fuzzy numbers (Chen and Hwang, 1992). We defined the linguistic scale in Table 6.

According to Miller (1956) and Norris (1998), for an appropriate judgment for the linguistic term selection is between 5 and 9 (Miller, 1956; Norris, 1998). Therefore, 7 fuzzy linguistic scale is determined for this study. Trapezoidal fuzzy numbers are used for FFTA (Senol, 2014).

A heterogeneous expert group is preferred for the expert consultation. As they have rich backgrounds and different experiences

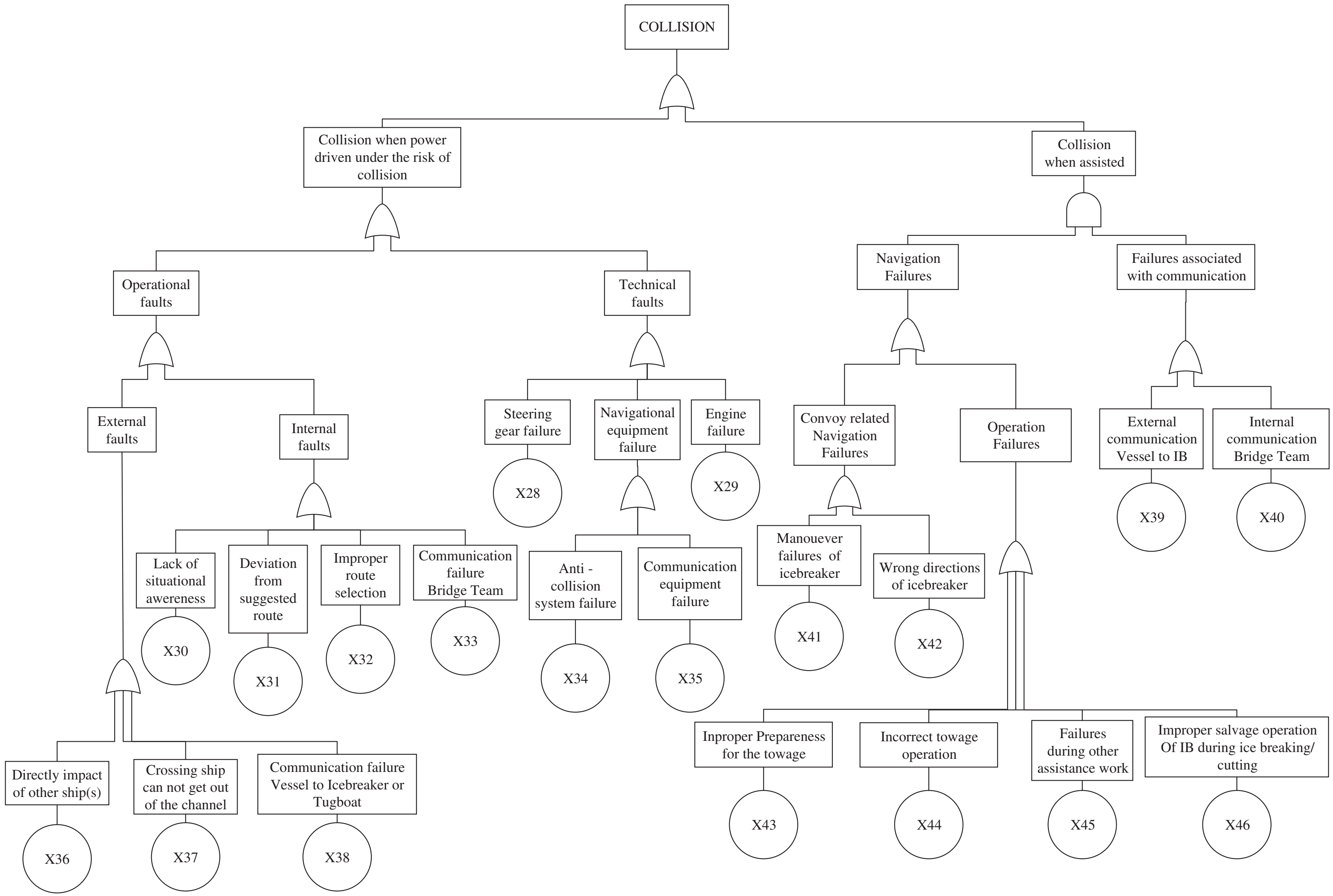

Fig. 11. Fault tree of collision.

Table 6
The scale of fuzzy sets.

Linguistic expressions	Fuzzy numbers
Very Low (VL)	(0, 0, 0.1, 0.2)
Low (L)	(0.1, 0.2, 0.2, 0.3)
Mildly Low (ML)	(0.2, 0.3, 0.4, 0.5)
Medium (M)	(0.4, 0.5, 0.5, 0.6)
Mildly High (MH)	(0.5, 0.6, 0.7, 0.8)
High (H)	(0.7, 0.8, 0.8, 0.9)
Very High (HV)	(0.8, 0.9, 1, 1)

Table 7
Professions and Experience of the Experts.

No of experts	Professional position	Sea service time (year)	Shore service time (year)	Educational level	Weighting factor	w
1	Academician	3–5	11–15	PhD	15	0.13
2	Academician	3–5	5	PhD	13	0.11
3	Academician	3	5	PhD	12	0.10
4	Academician	3	5	PhD	12	0.10
5	Academician	11–15	11–15	MSc	16	0.13
6	Master	16	16–25	PhD	16	0.13
7	Master	6–10	5	MSc	10	0.08
8	Master	6–10	5	BS	9	0.08
9	Chief Officer	3–5	6–10	PhD	10	0.08
10	Chief Officer	6–10	5	BS	7	0.08

Table 8
$\tilde{R}_u = (r_{u1}, r_{u2}, r_{u3}, r_{u4})$ experts opinions for BE X40.

Experts	Opinions of experts			
	r_{u1}	r_{u2}	r_{u3}	r_{u4}
E1	0.0	0.0	0.1	0.2
E2	0.0	0.0	0.1	0.2
E3	0.2	0.3	0.4	0.5
E4	0.2	0.3	0.4	0.5
E5	0.0	0.0	0.1	0.2
E6	0.0	0.0	0.1	0.2
E7	0.1	0.2	0.2	0.3
E8	0.7	0.8	0.8	0.9
E9	0.8	0.9	1.0	1.0
E10	0.5	0.6	0.7	0.8

Table 9
Similarity functions.

No	Similarity function	Similarity function value	No	Similarity function	Similarity function value	No	Similarity function	Similarity function value
1	S(E1&E2)	1	16	S(E2&E9)	0.15	31	S(E5&E6)	1
2	S(E1&E3)	0.725	17	S(E2&E10)	0.425	32	S(E5&E7)	0.875
3	S(E1&E4)	0.725	18	S(E3&E4)	1	33	S(E5&E8)	0.275
4	S(E1&E5)	1	19	S(E3&E5)	0.725	34	S(E5&E9)	0.15
5	S(E1&E6)	1	20	S(E3&E6)	0.725	35	S(E5&E10)	0.425
6	S(E1&E7)	0.875	21	S(E3&E7)	0.85	36	S(E6&E7)	0.275
7	S(E1&E8)	0.275	22	S(E3&E8)	0.55	37	S(E6&E8)	0.275
8	S(E1&E9)	0.15	23	S(E3&E9)	0.425	38	S(E6&E9)	0.15
9	S(E1&E10)	0.425	24	S(E3&E10)	0.7	39	S(E6&E10)	0.425
10	S(E2&E3)	0.725	25	S(E4&E5)	0.725	40	S(E7&E8)	0.4
11	S(E2&E4)	0.725	26	S(E4&E6)	0.725	41	S(E7&E9)	0.275
12	S(E2&E5)	1	27	S(E4&E7)	0.85	42	S(E7&E10)	0.55
13	S(E2&E6)	1	28	S(E4&E8)	0.85	43	S(E8&E9)	0.875
14	S(E2&E7)	0.875	29	S(E4&E9)	0.425	44	S(E8&E10)	0.85
15	S(E2&E8)	0.275	30	S(E4&E10)	0.7	45	S(E9&E10)	0.725

Table 10
Average and relative agreement of experts.

Average agreement of experts (AA)		Relative agreement of experts (RA)	
E1	0.686	E1	0.11
E2	0.686	E2	0.11
E3	0.713	E3	0.12
E4	0.713	E4	0.12
E5	0.686	E5	0.11
E6	0.619	E6	0.10
E7	0.647	E7	0.10
E8	0.480	E8	0.08
E9	0.369	E9	0.06
E10	0.580	E10	0.09

Table 11
Consensus coefficient.

Consensus coefficient (CC)	
CC1	0.1206
CC2	0.1076
CC3	0.1012
CC4	0.1012
CC5	0.1250
CC6	0.1196
CC7	0.0958
CC8	0.0779
CC9	0.0733
CC10	0.0773

Table 12
Aggregation of BE X40.

Aggregation of BE X40			
0.2020	0.2547	0.3373	0.4300

Table 13
Defuzzification.

BEs	Defuzzification of BEs (CFP)	BEs	Defuzzification of BEs (CFP)
X01	0.625	X24	0.672
X02	0.789	X25	0.585
X03	0.679	X26	0.569
X04	0.841	X27	0.505
X05	0.841	X28	0.178
X06	0.870	X29	0.211
X07	0.861	X30	0.228
X08	0.843	X31	0.161
X09	0.861	X32	0.171
X10	0.880	X33	0.225
X11	0.420	X34	0.254
X12	0.617	X35	0.226
X13	0.813	X36	0.265
X14	0.766	X37	0.265
X15	0.819	X38	0.301
X16	0.679	X39	0.380
X17	0.742	X40	0.307
X18	0.695	X41	0.380
X19	0.663	X42	0.290
X20	0.824	X43	0.303
X21	0.500	X44	0.301
X22	0.845	X45	0.324
X23	0.848	X46	0.338

Table 14
Conversion of CFP into failure probability.

BEs	FP of BEs	BEs	FP of BEs	BEs	FP of BEs
X01	0.01147	X17	0.02417	X33	0.00017
X02	0.03293	X18	0.01785	X34	0.00050
X03	0.01620	X19	0.01459	X35	0.00034
X04	0.04789	X20	0.04221	X36	0.00059
X05	0.04789	X21	0.00500	X37	0.00060
X06	0.06045	X22	0.04939	X38	0.00090
X07	0.05586	X23	0.05056	X39	0.00197
X08	0.04884	X24	0.01549	X40	0.00092
X09	0.05614	X25	0.00889	X41	0.00200
X10	0.06567	X26	0.00800	X42	0.00080
X11	0.00275	X27	0.00850	X43	0.00092
X12	0.01094	X28	0.00014	X44	0.00090
X13	0.03895	X29	0.00026	X45	0.00114
X14	0.02837	X30	0.00035	X46	0.00132
X15	0.04072	X31	0.00010		
X16	0.01622	X32	0.00012		

on particular subjects of Arctic region, they are not assigned equal weights which is given on Table 7.

6.2. Aggregation stage

The aggregation process is completed in this stage after all experts' decisions. Consensus coefficient is obtained after the β value is set as 0.5 for each experts. To clarify the aggregation process, BE 40 *Internal Communication Failure* for the collision when assisted as an example, is given in Tables 8–12.

6.3. Defuzzification of subjective BEs

For this study, center of area defuzzification method is applied to the problem. Defuzzification results of all BEs are indicated in Table 13.

Table 16
Sensitive analysis of the first 10 MCSs.

TE for collision = 0.00411489; TE for grounding = 0.007525782		
No of MCS	Occurrence probability of MCS	F-VIM
X38	9.028E−04	21.94
X36	5.906E−04	14.35
X37	5.906E−04	14.35
X34	5.088E−04	12.37
X10X12	7.187E−04	9.55
X30	3.529E−04	8.58
X35	3.395E−04	8.25
X12X9	6.144E−04	8.12
X10X13X17	6.185E−05	7.10
X29	2.680E−04	6.51

6.4. Conversion of Crisp Failure Possibilities (CFP) to Failure Probability (FP)

CFPs are converted into FP, which is shown in Table 14. FP is calculated after obtaining all FBs of all BEs. The basic probability operations are applied to the calculation by considering the logic gates. Then, the FP of Top Event (TE) is calculated.

FP of TE is calculated as for collision 4.114890E−003 (~0.004) for grounding 7.525782E−003 (~0.008) after all calculations. MCSs and list of Fussell–Vesely Importance Measurement (F-VIM) are shown in Tables 15 and 16. The results are compared to the reality by asking field experts. They agree that the results are reasonable under these frameworks.

6.5. Calculation FP of TE

In this stage, after the application of Generic FTA, the FPs of all BEs are determined and then the probability of TE is calculated. List of first ten MCSs is provided in Table 16.

Table 15
Occurrence probabilities of MCSs.

MCSs	Probability	MCSs	Probability	MCSs	Probability
X38	9.029E−04	X13X20X7	9.187E−05	X13X26X8	1.523E−05
X10X12	7.187E−04	X13X20X8	8.032E−05	X10X13X21	1.279E−05
X12X9	6.144E−04	X10X13X17	6.185E−05	X13X21X9	1.093E−05
X12X7	6.114E−04	X13X17X9	5.287E−05	X13X21X7	1.088E−05
X36	5.906E−04	X13X17X7	5.262E−05	X13X21X8	9.514E−06
X37	5.906E−04	X13X17X8	4.600E−05	X39X41	3.886E−06
X12X8	5.346E−04	X10X13X18	4.566E−05	X39X46	2.620E−06
X34	5.089E−04	X10X13X24	3.963E−05	X39X45	2.266E−06
X30	3.529E−04	X13X18X9	3.904E−05	X40X41	1.826E−06
X35	3.396E−04	X13X18X7	3.885E−05	X39X43	1.826E−06
X29	2.690E−04	X10X13X19	3.734E−05	X39X44	1.775E−06
X10X11	1.808E−04	X13X24X9	3.388E−05	X39X42	1.577E−06
X33	1.721E−04	X13X18X8	3.396E−05	X40X46	1.231E−06
X11X9	1.546E−04	X13X24X7	3.371E−05	X10X14X15X16	1.231E−06
X11X7	1.538E−04	X13X19X9	3.192E−05	X40X45	1.064E−06
X28	1.438E−04	X13X19X7	3.176E−05	X14X15X16X9	1.052E−06
X11X8	1.345E−04	X13X24X8	2.948E−05	X14X15X16X7	1.047E−06
X32	1.297E−04	X13X19X8	2.777E−05	X14X15X16X8	9.155E−07
X10X13X23	1.294E−04	X10X13X25	2.277E−05	X40X43	8.578E−07
X10X13X22	1.264E−04	X10X13X27	2.189E−05	X40X44	8.341E−07
X13X23X9	1.106E−04	X10X13X26	2.048E−05	X40X42	7.413E−07
X13X23X7	1.100E−04	X13X25X9	1.947E−05	X1X10X2X4X5X6	3.440E−09
X13X22X9	1.080E−04	X13X25X7	1.937E−05	X1X2X4X5X6X9	2.941E−09
X10X13X20	1.080E−04	X13X27X9	1.871E−05	X1X2X4X5X6X7	2.926E−09
X13X22X7	1.075E−04	X13X27X7	1.862E−05	X1X2X4X5X6X8	2.559E−09
X31	1.028E−04	X13X26X9	1.750E−05	X1X10X3X4X5X6	1.692E−09
X13X23X8	9.621E−05	X13X26X7	1.742E−05	X1X3X4X5X6X9	1.446E−09
X13X22X8	9.399E−05	X13X25X8	1.694E−05	X1X3X4X5X6X7	1.439E−09
X13X20X9	9.232E−05	X13X27X8	1.628E−05	X1X3X4X5X6X8	1.259E−09

The results for the probabilities of collision (approx. 0,004) and grounding (approx. 0.008) seem low at the first sight. However, in the case of occurrence such an accident, its both short-term and long-term effects to human lives, environment, politics and economy might be too costly. Therefore, occurrence probabilities of each root causes should be minimized by taking all possible precautions.

7. Conclusions

Marine accident analyses are performed by many scholars and non-profit organizations for many years. However, analysis of ice navigation has many differences than the regular navigation. In this study, a review is conducted on available data for the marine incidents occurring in the Arctic Region. The most comprehensive data are found as a source is determined to be the MAIB. Root cause analysis of marine incidents occurring in the Arctic region is the novelty of this study which charts out the root causes of the events based on the 65 reported incidents between the years 1993 and 2011. Data explanation is performed in a careful manner. Accident to Person is observed as the most occurring accident and there are 13 root causes regarding to negligence/careless of injured people which have the highest priority for root causes of marine accidents. Some of the limitations of this study were that this study is conducted under lack of data availability and limited number of field experts. Accordingly, these analyses can differentiate based on the individual perspectives.

A fuzzy fault tree approach is carried out as an empirical study considering the marine accidents occurring in the Arctic region wherein the objective is to minimize the risk of re-occurrence by identifying the critical minimal cut sets in the system. Classification of the root causes for grounding and collision occurring in the Arctic region is conducted after logical relations are established. The structures of fault trees for grounding and collision are constructed, by using linguistic variables, the ambiguities are handled and occurrence probabilities of hazards (basic events) are determined. In order to remove the vagueness nature of the system, instead of using crisp failure possibility, failure probability is preferred to determine the numerical risk levels of each causes after completing several expert consultations. Safety performance of a system can be improved by using the importance measure therefore, Fussell–Vesely importance measure index is determined to identify the critical minimal cut sets in order to reduce the occurrence likelihood of a top event.

The results indicate the significance of crew training and competence requirements and as well as more Arctic navigation training centers. The analysis proves that safety is a real problem in the Arctic region and marine accident analysis is a significant gap for the researchers. Fault Tree Analysis for the other ice-navigation-related failures such as icing, stuck in ice, machinery failures and similar accidents are the research gaps to be developed for the Arctic region. Similarly, academic studies for risk assessment of the Arctic navigation should be carried out.

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Appendix A

The main data sources for marine accidents:
Global Integrated Shipping Information System (GISIS).
IMO MSC-MEPC.3/Circ.3, IMO FSI 20/INF.17.
FSI, IMODOCS, IMO Performance Indicators.
International Shipping Facts and Figures – Information.
Resources on Trade, Safety, Security and the Environment.
Lloyd's Casualty Returns available from Lloyd's Register Library.
LMIU Casualty Reports, IHS Fairplay World Casualty Statistics.
International Union of Marine Insurers (IUMI).
European Maritime Safety Agency: Annual Maritime Accident Review.
ShipPax Information.
Marine Casualty Profiles International Maritime Statistics Forum.
Wally Mandryk Lloyds List Intelligence.
Australian Transport Safety Bureau (ATSB).
Transportation Safety Board of Canada (TSBC).
BEAmer- The Bureau d'enqutes sur les vnements de mer.
Dutch Transport Safety Board.
Transport Accident Investigation Commission (TAIC).
Swedish Accident Investigation Board (SHK).
UK Marine Accident Investigation Branch (MAIB).
Marine Accident Reporting Scheme (MARS).
US National Transportation Safety Board (NTSB).

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