A comprehensive analysis for collision and grounding accidents by using a hybrid FTA-FUCOM-ETA method

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Abstract: The main contribution of this study is to analyse the causes of navigational accidents, regardless of the type of ship, and to investigate by using a hybrid fault tree analysis, full consistency method, and event tree analysis. We determine the accidents and their known causes between the years of 2014 and 2020 according to IMO GISIS data. Sensitivity analyses are conducted for the operational and unsafe action failures. For collisions, non-compliance with the COLREGs, insufficient lookout, storms, strong winds, and narrow manoeuvre areas causes are found to be the most critical causes. For grounding, heavy weather conditions, insufficient lookout, engine failure, strong winds, and loss of power are the top causes that the countermeasures should be taken. Inspections for the training centres, education of maritime English, more recruitment of seafarers to reduce the workload, and usage of information technology for weather incidents are recommendations for some of the managerial implications.

Keywords: maritime accidents; collision; grounding; fault tree analysis; FTA; full consistency method; FUCOM; event tree analysis; ETA.

Reference to this paper should be made as follows: Aslan, B., Sahin, B. and Yazir, D. (2024) 'A comprehensive analysis for collision and grounding accidents by using a hybrid FTA-FUCOM-ETA method', *Int. J. Shipping and Transport Logistics*, Vol. 18, No. 4, pp.449–490.

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1 Introduction

Maritime activities are carried out in all seas and inland waters of the world. In addition, the contribution of maritime transportation to world trade is quite high. Approximately 90% of transportation is carried out via waterways (Ece et al., 2020). Therefore, various sea incidents are experienced both during the realisation of maritime activities and during maritime transportation. The most important of the incidents experienced while maritime activities are carried out is the ship accidents with the greatest impact. Ship accidents adversely affect the cargo carried by the ship, the personnel working on the ship, and the environment. Although many conventions, rules, and standards have been introduced to prevent ship accidents from happening, tragedies continue to occur (Yildirim et al., 2015).

When examining the history of the rules created to prevent ship accidents, almost every rule is amended after an accident. For example, safety of life at sea (SOLAS) was adopted after the Titanic ship accident. However, insufficient compliance with these rules and human-induced reasons are among the most important causes of ship accidents (Yildirim and Basar, 2019).

Many ship accidents have occurred until today. While some of these accidents did not cause any damage or loss, some serious losses and damage occurred. Table 1 is created by compiling the major accidents that occurred in the world and caused serious damage (Deniz Haber, 2011; Gokcek, 2011).

In their document of International Maritime Organization (IMO) and Marine Accident Investigators' International Forum (MAIIF), types of ship accidents, navigation accidents (collision, grounding, contact and allision), fires and explosions, cargo shift incidents, flooding, foundering, lifesaving appliances and evacuation structural, machinery, equipment failure, ship lost or missing accidents involving enclosed/confined spaces accidents have been indicated (MAIIF, 2014).

When ship accidents are examined, the most common type of accident is navigation-related accidents. MAIIF defines navigational accidents as collisions and groundings. Most of the studies on ship accidents, it has been determined that the accidents are commonly examined according to the ship type, region, and accident type.

Table 1 Major ship accidents and their damages

Ship name	*Accident year*	*Accident area*	*Accident type*	*Loss of life/damage*
HMS Captain	1870	Biscay Bay	Sinking	482 deaths
Titanic	1912	Newfoundland	Collision/Allision	1,513 deaths
SS Morro Castle	1934	USA	Fire	137 deaths
Dumlupınar	1953	Çanakkale Strait	Collision/Allision	81 deaths
SS Andrea Doria	1956	Atlantic Ocean	Collision/Allision	46 deaths
Lakonia	1963	Canary Islands	Fire	128 deaths
Torrey Canyon	1967	Scillia Islands	Grounding	120,000 tons of oil are spilled into the sea
Amoco Cadiz	1978	Brittany/France	Collision/Allision	220,000 tons of oil are spilled into the sea
Independenta	1979	Istanbul Strait	Collision/Allision	43 deaths and 95,000 tons of oil are spilled into the sea
Dona Paz	1987	Philippines	Collision/Allision	4,375 deaths
Herald of Free Enterprise	1987	English Channel	Sinking	193 deaths
Exxon Valdez	1989	Alaska	Sinking	440 tons of oil are spilled into the sea
Estonia	1994	Baltic Sea	Sinking	852 deaths
Nassia	1994	Istanbul Strait	Collision/Allision	30 deaths and 20,000 tons of oil are spilled into the sea
Erika	1999	France	Sinking	31,000 tons of oil are spilled into the sea
Prestige	2002	Atlantic Ocean	Sinking	77,000 tons of oil are spilled into the sea
El Selam Boccaccio 98	2006	Red Sea	Sinking	1,000 deaths
MSC Napoli	2007	France	Sinking	2,394 containers, 42,000 tons of commercial goods, 1,700 tons of chemicals and 3,000 tons of load and oil are spilled into the sea
Volgoneft-139	2007	Kerch Strait	Sinking	1,300 tons of oil are spilled into the sea
Princess of the Stars	2008	Philippines	Sinking	690 deaths

As far as known, in the literature, there is no comprehensive study that deals with the causes, consequences, and solution suggestions for collision and grounding as maritime accidents. The research gaps and motivation of this study are to analyse the comprehensive data from the database of a top organisation (IMO-GISIS), and report the causes, consequences, and solution suggestions of maritime accidents. In this study,

accidents that occurred between 2014–2020 and whose causes are known according to IMO GISIS are determined, and the causes of navigation-related accidents, regardless of the ship type, are examined with a hybrid FTA-FUCOM-ETA method.

The paper continues as follows. Section 2 reviews the literature. Section 3 gives the data collection and proposed method. Application is done in Section 4. Section 5 discusses the results and limitations. Finally, the last section concludes the paper.

2 Literature review

The number of studies about the accidents occurring at sea is quite high (Senol et al., 2015; Sahin et al., 2021). Different methods in the studies are used to examine ship accidents and determine the root causes. In addition, considering these studies, various accident types are examined such as technology selection, crankcase explosion, ontology-based systems, strategic management, improvements of fault tree analysis (FTA) and model development (Senol and Sahin, 2016; Sahin and Yip, 2017; Sahin, 2017; Ünver et al., 2019; Sahin et al., 2021) and risk assessments are made for some special operational works.

Grounding and collision accidents in load cargo and general cargo ships between 2008–2018 are examined in the study conducted by Tuncel (2020). The causes of 48 collisions and 25 grounding accidents are examined by FTA. It has been determined that COLREG interpretation error in collision settlement accidents and lack of communication with bridge resource management in grounding accidents are the most important reasons. Puisa et al. (2018) investigated the causal factors of maritime accidents. As a result of the examination, it was emphasised that knowing where the weak link causing maritime accidents is, what its role is in the cause of the accident and how it can be eliminated can reduce the risk in accidents. In another study, 60 maritime accidents in the Gulf of Mersin between 2001–2016 are investigated by implementing FTA method. In the study, it has been stated that Human error 83%, collision and contact 28% are effective in accidents (Buber et al., 2018). Fu et al. (2022) quantitatively analysed the grounding accidents during maritime activities in arctic waters. The AcciMap model was developed to describe the development of accidents and to show the interdependence of risk factors. The causes of 62 grounding accidents that occurred in the Çanakkale Strait between 2000–2011 are investigated by FTA. In the study, among the causes of a grounding accident, human error is stated the most (Kilic and Sanal, 2015). Wróbel (2021) investigates whether human error reflects the reality in accidents occurring in maritime environment. As a result, it has been determined that human error has a significant contribution to accidents. However, the contribution rate is less than the generally accepted 80% rate. In the study carried out by Mentes and Helvacioglu (2010), the risks are investigated by using FTA for the risk analysis of multi-point tanker buoy systems. With the data obtained in the study, a method has been proposed for the detailed risk analysis and the determination of error probabilities.

The main causes of fire and explosion accidents between 1990–2015 are examined. The study provides information on the causes and prevention of accidents to reduce the risk of fire and explosion in the maritime field (Baalisampang et al., 2018). The system using failure mode and impact analysis, hazard identification, hazard operability and FTA to evaluate the reliability of the liquefied natural gas transfer system, to identify possible dangers and to take precautions has been analysed. Detailed security with the data

obtained evaluation example is presented (Lee et al., 2017). The accidents that occurred in a hybrid process engine room including human factors analysis and classification system and fuzzy FTA (FFTA) are investigated. It has been stated that fire-explosion accidents are more common in ships over 20 years old and mechanical faults are effective in the accident (Sarialioğlu et al., 2020). In another study, fire accidents in the natural gas industry are investigated with FTA and event tree analysis (ETA). With the data obtained in the study, a different methodology has been proposed for the risk assessment for the business (Hosseini et al., 2019). Similarly, fire accidents in the natural gas industry are investigated with FTA and ETA. With the data obtained in the study, a different methodology has been proposed for the risk assessment for the business (Wang et al., 2021).

The maintenance of Ro-Ro ships is carried out in order for ship survey and maintenance to reach their targets and Survey results are analysed by risk-based inspection (RBI) method. In addition, the results of the risk are obtained with FMEA and FTA method. In the study, it is stated that the RBI method is examined 20% of all parts and the failure risk of the remaining 80% could be reduced (Putra et al., 2020). In another study, the suggestions to examine the causes of collision, grounding and contact type accidents in Bangladesh are given after implementing with FTA (Awal et al., 2014). Another marine accident is investigated by using FFTA to perform risk analysis of ship mooring operations. In that study risk control options are proposed by developing a risk model (Kuzu et al., 2019). According to Kim et al. (2017), the causes of the accidents on the fishing boats are examined with FTA. In the study, due to carelessness and negligence in the shift the occurrence possibility of actual accidents is found to be 64.9%. In this possibility, it is stated that human error is less than media factors and management factors. In addition, it is emphasised that not only human error but also media and management factors should be taken into account in order to reduce accidents.

Guidelines for reducing the damage caused by accidents and investigating the causes of accidents methods are presented in Baten (2018). Mallam et al. (2022) conducted a study on how officers should evaluate maritime accident reports. As a result, the rate of evaluation of accident reports by officers was low. In the study, suggestions were presented for the use of the reports by the officers. The causes of ten tanker accidents that occurred during loading and unloading between 2000 and 2014 are examined with FTA. Failure to comply with the procedure and lack of information are identified as important reasons in the study (Arslan et al., 2018). Forty six maritime accidents between 2010 and 2018 are examined by exploratory statistical analysis. It is stated that environmental factors and day/night are effective in ship accidents (Karaca and Söner, 2020). Errors that may occur on the lathe are examined with FTA. In the study, it is aimed to determine the design criteria and maintenance recommendations (Waghmode and Patil, 2013).

When the studies are examined, the accident type, ship type, specific region, specific time period or accidents that occurred in some operational works are carried out separately or by combining several factors. As a result of the data obtained in this study, it has been examined by taking into consideration navigational accidents from accidents in the world seas. In addition to that, all ship types involved in the accident have been taken into account between the dates given.

3 Data collection and proposed method

The data used in the study are taken from IMO GISIS. All the accident records in the system, between January 2014 and March 2020 are examined. From these accident records, 230 accidents have been used in the study of which accidents caused by navigation where their causes are known. 110 of the 230 accidents are grounding and 120 of the accidents are collisions. The data in different categories are combined, merged, filtered, and cleaned as pre-process operations by using data processing sheets. As a result of the data preparation procedure, the causes and sub-causes of the accidents are determined and arranged in detail to be examined by the FTA method.

3.1 Fault tree analysis

FTA method is one of the most used methods in risk assessment methods and finding the root causes of errors (Kum and Sahin, 2015). FTA method is used in this study which is the determination of the main causes of an undesired event or situation and expressing it in a diagram. All the reasons that will cause a threat are identified. In this method, it is aimed to minimise or prevent risky situations by revealing all the sub-causes of the event. It can be expressed that FTA is the most important method that has been used in security analysis since the 1960s. It is also an effective method in the analysis of complex systems (Lee et al., 1985; Harms-Ringdahl, 2001; Ozkilic, 2005; Kim et al., 2020; Yalcinkaya et al., 2020).

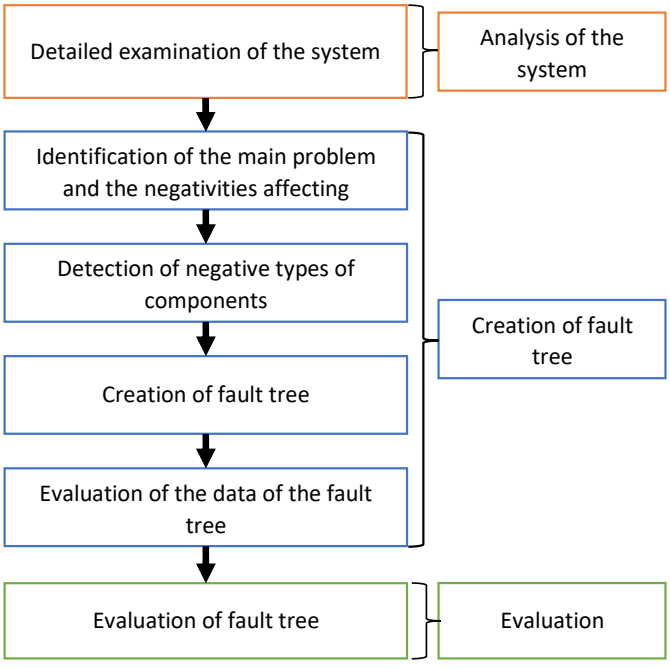
FTA method basically consists of three stages which are analysis of the system, creation of fault tree (FT) and the evaluation (Figure 1).

In the FTA method, a diagram is created by using symbols and gates. The basic symbols used in FTA are given in Table 2.

Crisp and fuzzy evaluations can be realised in the FTA method. FTA has the capacity to conduct qualitative and quantitative analyses (Ozkilic, 2005). Quantitative analysis is the quantitative determination and examination of the causes and sub-causes which are listed in the FT. In FTA, each cause and sub-cause must be usable in practice. A relationship is established between the probabilities which have been determined by the quantitative analysis used in FTA, the causes, and the upper events. With this relationship, the occurrence of the upper event is calculated quantitatively. Qualitative analysis is the qualitative examination of the causes and sub-causes which are listed in the FT. In FTA, the data obtained because of the calculations made with quantitative analysis are interpreted and the relationship between the causes of the upper event is explained with qualitative analysis.

The main cause, whose probability of occurrence is examined, is defined as the upper event. The event that affects the realisation of the upper event and cannot be divided into sub-causes is defined as the main/BE. The ‘AND’ gate, one of the gates in the FTA, indicates that the event will occur if the events under it occur simultaneously. At the ‘OR’ gate, the occurrence of any of the underlying causes is sufficient for the event to occur. In FTA, the terms cut set, MCSs and path set are used to help interpret the results. Cut set refers to any group of FTs, declaring that the upper event will occur if all of them occur. MCS refers to the smallest group of FTs, declaring that the upper event will occur if all of them occur. Path set is defined as the group that starts the FT. When the causes in this group do not occur, the upper event does not occur (Yalcinkaya et al., 2020).

Figure 1 Stages of analysing FT (see online version for colours)



Source: Ozkilic (2005)

Table 2 Basic symbols used in FTA

Symbol	*Marked*	*Function*
	Basic event (BE)	BE/failure
	Event	Event consisting of more BEs
	AND gate	Indicates that the output event has been consisted of the simultaneous occurrence of all input events under this gate
	OR gate	Indicates that the output event has been consisted by any input event
	Transfer symbol (in/out)	Indicates that the tree is developed further at another place

As a result of the data obtained based on this information, the causes and sub-causes of the accident have been determined and arranged to be examined by FTA. Data about the success and errors of the system are obtained by considering the events that took place. As a result of the data obtained, the reliability of the system and the probability of error are calculated with equations (1) and (2).

$$R = \frac{S}{(S+F)} \tag{1}$$

$$P_F = \frac{F}{(S+F)} \tag{2}$$

$$R + P_F = \frac{S}{(S+F)} + \frac{F}{(S+F)} = 1 \tag{3}$$

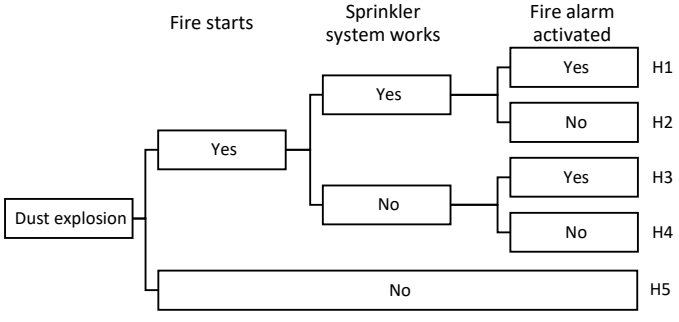
where S, F, R, P_F represent successes, failures, reliability, and probability of failure/failure probability, respectively. Necessary calculations are made by writing the obtained probability values in the FT.

3.2 Full consistency method

Full consistency method (FUCOM) is a multi-criteria decision-making method for subjective weighting which is developed by Pamučar et al. (2018). Two conditions must be met for the weight coefficients to provide the most appropriate values. The first condition is that the relationships between the weighting coefficients of the criteria must be equal to the comparative priorities of the criteria. In the second condition, the weight coefficients obtained must satisfy the mathematical transitivity condition. To check this condition, the degree of complete consistency deviation (CCD) is checked. The CCD degree is the deviation of the weight coefficients obtained from the estimated comparative priorities of the criteria. CCD also indicates that the criterion weights obtained are reliable. When the CCD value is in the range of [0, 0.025], the weighting coefficients are acceptable or close to optimal values (Demir and Bircan, 2020; Ecer, 2021).

The FUCOM method is applied according to the following steps (Demir and Bircan, 2020; Ecer, 2021).

Figure 2 Event tree diagram



Source: Harms-Ringdahl (2001)

Decision makers rank the criteria. Ranking is done from the most important criterion to the least important criterion. If there are two or more criteria with the same importance, the '=' sign is placed between these criteria instead of the '>' sign.

$$C_{j(1)} > C_{j(2)} > \ldots > C_{j(k)} \tag{4}$$

The decision maker compares the listed criteria. The comparative priorities of the criteria ($\varphi_{(k/(k+1))}$) are determined. Here, the advantage of ranking $\varphi_{(k/(k+1))}$ and $C_{j(k)}$ criterion over

the ranking of $C_{j(k+1)}$ criterion is determined. Thus, vectors of comparative priorities of evaluation criteria are obtained.

$$\Phi = \left(\varphi_{1/2}, \varphi_{2/3}, \varphi_{3/4}, \ldots, \varphi_{k/(k+1)}\right) \tag{5}$$

In order to compare the criteria, the decision makers can determine the importance of each criterion with a determined measurement scale (such as 1–9 scale) or it can be determined by considering the characteristics of the observed criteria (mass weights). The final values of the weighting coefficients of the evaluation criteria are calculated (w_1, w_2, …, $w_n)^T$. The final values of the weight coefficients must satisfy the following two conditions:

- Condition 1: The ratio of the weighting coefficients must be equal to the comparative priority $\varphi_{k/(k+1)}$ between the observed criteria.

$$\frac{w_k}{w_{k+1}} = \varphi_{k/(k+1)} \tag{6}$$

- Condition 2: The final values of the weight coefficients must satisfy the mathematical transitivity condition of $\varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} = \varphi_{k/(k+2)} \cdot \varphi_{k/(k+1)} = w_k/w_{(k+1)}$. Also, $\frac{w_k}{w_{k+1}} \otimes \frac{w_{k+1}}{w_{k+2}} = \frac{w_k}{w_{k+2}}$ is obtained from $\varphi_{(k+1)/(k+2)} = \frac{w_{k+1}}{w_{k+2}}$. Thus, another condition that the final values of the weighting coefficients of the evaluation criteria must fulfil is obtained as in equation (7).

$$\frac{w_k}{w_{k+2}} = \varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} \tag{7}$$

The minimisation of the weight coefficients (w_1, w_2, …, $w_n)^T$, the DFC (χ) values $\left|\frac{w_k}{w_{(k+1)}} - \varphi_{\frac{k}{(k+1)}}\right| \le \chi$ and $\left|\frac{w_k}{w_{(k+2)}} - \varphi_{\frac{k}{(k+1)}} \otimes \varphi_{\frac{(k+1)}{(k+2)}}\right| \le \chi$ should be realised to meet the conditions.

3.3 Event tree analysis

ETA expresses the consequences that may arise after the occurrence of a determined event with a horizontal diagram (Figure 2). It differs from FTA in that it uses inductive logic. This analysis can be applied qualitatively or quantitatively. In the ETA, the starting event is on the right, the decision or action point is on the top, and the result places on the left (Ozkilic, 2005; TSE, 2010; Barozzi et al., 2021).

4 Application

4.1 FTA

The data related to the accidents and their causes have been arranged and made ready for examination with FTA. The analysis of the obtained data with FTA has been examined in five steps.

Step 1 Organising the data, determining the causes and sub-causes of the accidents.

Step 2 Calculation of probabilities of sub-causes.

Step 3 Creation of FT in the OpenFTA program.

Step 4 Entering and analysing probability values into the OpenFTA program.

Step 5 Evaluation of results.

In this study, equation (8) has been obtained by considering the basic calculations which are applied for the FTA method and the fault calculations have been encountered in the literature review. The probability values that have been calculated with equation (8) have been entered into the OpenFTA program and FTA has been performed.

$$\text{Probability of BE} = \frac{\text{Number of BEs}}{\text{Total number of accidents} \times \text{Number of vessels} \times \text{Year}} \tag{8}$$

The probability of a BE is the probability that the BE will occur. The number of BEs refers to the number of each event that has been determined as the main event in the accident. Total number of accidents is the total number of accidents that have been examined. The number of vessels is the total number of examined vessels that have been involved in the accident. Year refers to the year interval in which the examined accidents have occurred.

As an example, calculating the probability of lack of communication, one of the main events of the collision accident, is given in equation (9).

$$\begin{aligned} \text{Probability of BE} &= \frac{\text{Number of BEs}}{\text{Total number of accidents} \times \text{Number of vessels} \times \text{Year}} \\ &= \frac{3}{120 \times 201 \times 6.25} \\ &= 0.0000199 \end{aligned} \tag{9}$$

After organising the data, various statistical information about the accidents has been obtained. With this information, general information about the types of vessels that have been involved in the accident, the number of ships according to their gross size, the severity of the accidents, the number of vessels that have been involved in the accident by years, and general information about flags of these ships have been obtained. Then, FTs were created by calculating the probabilities of the determined sub-causes. The obtained data have been analysed.

Among the examined accidents, 120 accidents are collision accidents. A total of 201 ships have been involved in 120 collision accidents. Figure 3 shows the number of collision accidents by year. Since the accidents with known causes and until March 2020 are considered in the years examined (2014–2020) when creating Figure 3, the number of accidents for 2020 is low.

Ships involved in collision accidents have been classified according to their type. In general, 11 different ship types have been found. Small boats and service ships are classified as other ship types. Figure 4 has been created according to the classification result. According to Figure 4, the ship type most involved in collision accidents has been determined as general cargo type ships with 36 accidents.

Figure 3 Distribution of collision accidents by years (see online version for colours)

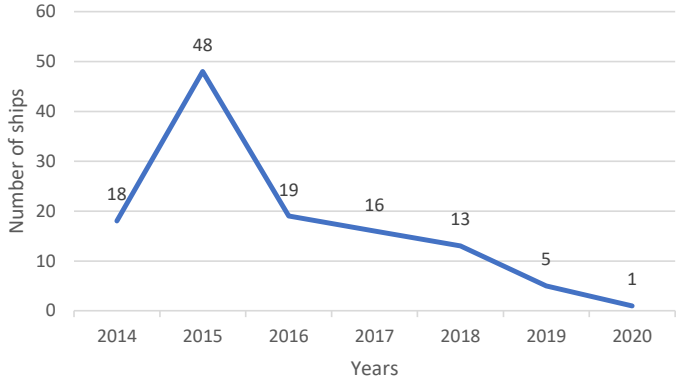


Figure 4 Number of ship types involved in collision accidents (see online version for colours)

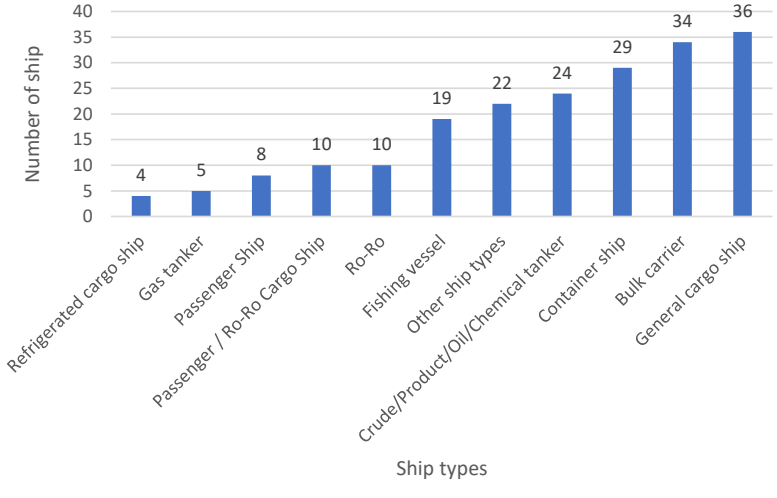


Figure 5 Distribution of grounding accidents by years (see online version for colours)

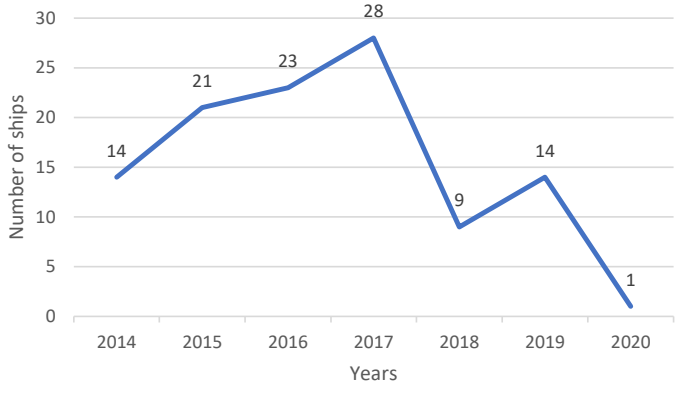
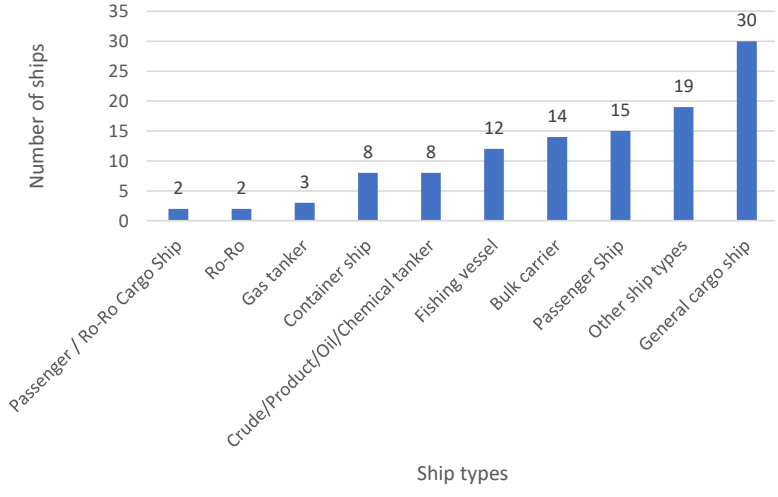


Figure 5 shows the number of grounding accidents by year. Since the accidents with known causes and until March 2020 are considered in the years examined (2014–2020) when creating Figure 5, the number of accidents for 2020 is low.

Ships involved in grounding accidents have been classified according to their type. In general, ten different ship types have been determined. Small boats and service ships are classified as other ship types. Figure 6 has been created according to the classification result. According to Figure 6, the ship type most involved in grounding accidents has been determined as general cargo type ships with 30 accidents.

Figure 6 Number of ship types involved in grounding accidents (see online version for colours)



As a result of the arrangements made, the data obtained are made to form a FT. Two separate FTs have been created for collision and grounding accidents and probability values are calculated. Equation (4) is used while calculating the probability values. The root causes of collision accidents are classified and the FT in Figure 7 is created. To see the FT as a whole, a coding system has been used. The explanations of the codes used, and the probabilities of the root causes are given in Table 3.

The root causes of grounding accidents are classified, and the FT in Figure 8 is created. The code is used to see the FT. The explanations of the codes used, and the probabilities of the root causes are given in Table 4.

As a result of the analysis made with OpenFTA software, the MCSs of collision accidents have been determined. As a result of the analysis, 968 MCSs have been found. In Table 5, MCSs and probabilities of events causing collision accidents are given. Since the number of MCSs is high, a total of 40 MCSs, 20 from the beginning and the end are given in Table 5. In addition, the probabilities of the MCSs are listed in Table 9 in order from largest to smallest.

Figure 7 FT for collision accidents (see online version for colours)

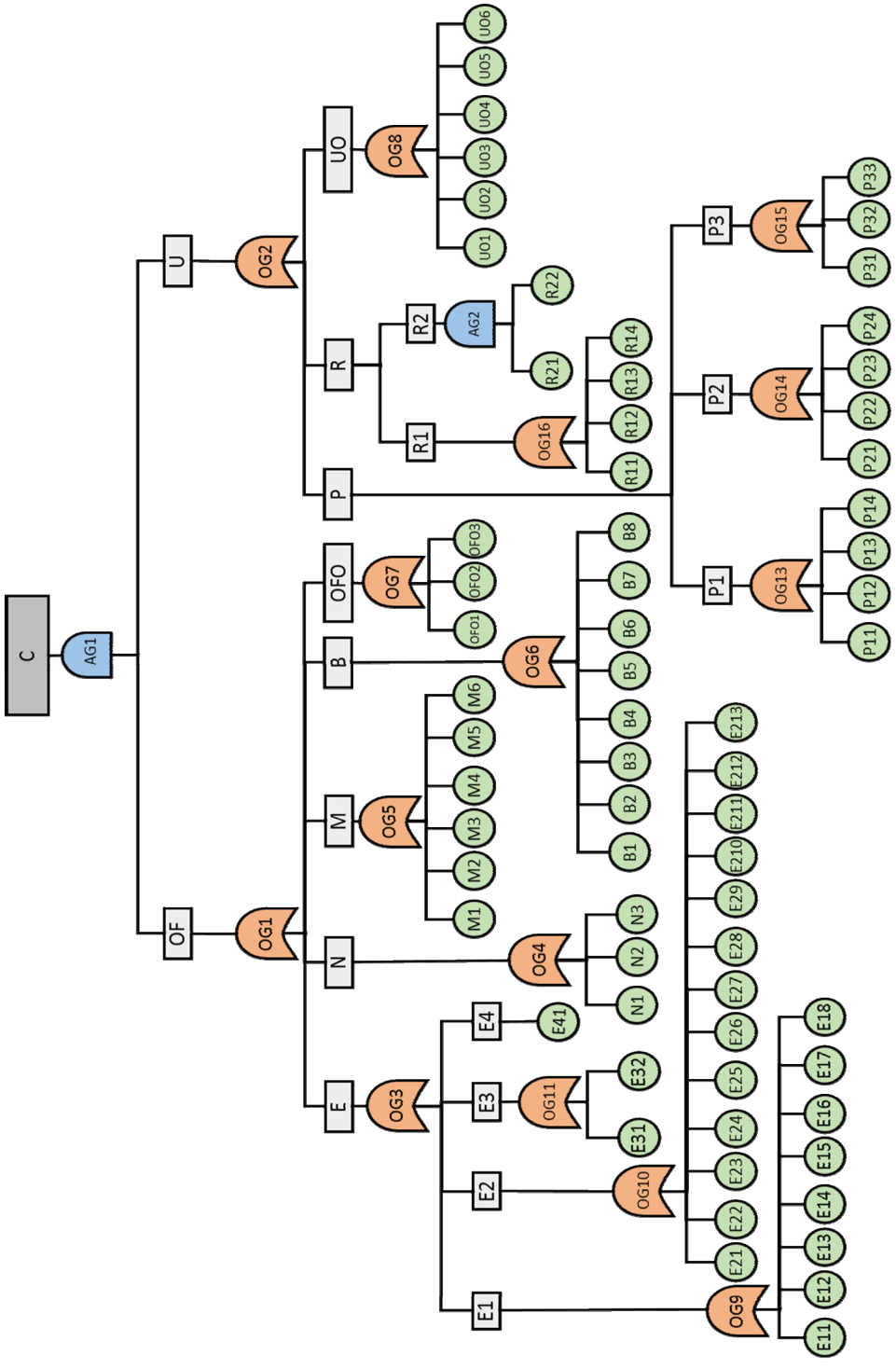


Table 3 Codes and probabilities of collision accidents

Code	*Description*	*Probability*
OF	Operational failures	
E	Equipment failures	
E1	Technical failures	
E11	Engine control system malfunction	6.63350E-06
E12	Engine failure	3.98010E-05
E13	Fault in the power control system	6.63350E-06
E14	Insufficient propulsion power	6.63350E-06
E15	Loss of control	6.63350E-06
E16	Loss of electrical power/blackout	6.63350E-06
E17	Loss of power	2.65340E-05
E18	Technical error	6.63350E-06
E2	Hardware errors	
E21	Break of rope	6.63350E-06
E22	Break of tug's rope	6.63350E-06
E23	CPP failure	6.63350E-06
E24	Gear failure	6.63350E-06
E25	Generator failure	6.63350E-06
E26	Hydraulic line malfunction	6.63350E-06
E27	Loss of steering ability	6.63350E-06
E28	Navigation equipment ceasing of signal transmission	6.63350E-06
E29	Radar failure	6.63350E-06
E210	Rope tangling to propeller	6.63350E-06
E211	Slow response of the CPP	6.63350E-06
E212	Steering failure	1.32670E-05
E213	Vessel does not respond the wheel	1.32670E-05
E3	Errors due to lack of equipment	
E31	Lack of equipment	6.63350E-06
E32	Lack of navigation equipment	6.63350E-06
E4	Other reasons	
E41	Diminution on the speed suddenly	6.63350E-06
N	Navigation failures	
N1	Contact with an unknown and uncharted object	6.63350E-06
N2	Shallow water	6.63350E-06
N3	Wrong navigation	6.63350E-06
M	Manoeuvring failures	
M1	Being late for manoeuvring action	3.31675E-05
M2	Narrow manoeuvre area	3.31675E-05
M3	Restricted manoeuvring	6.63350E-06

Table 3 Codes and probabilities of collision accidents (continued)

Code	*Description*	*Probability*
M4	Route change	6.63350E-06
M5	Short distance for manoeuvring action	6.63350E-06
M6	Wrong manoeuvre	4.64345E-05
B	Bad weather conditions	
B1	Dense fog	2.65340E-05
B2	Heavy rain	6.63350E-06
B3	Heavy weather conditions	2.65340E-05
B4	High waves	1.32670E-05
B5	Restricted visibility	1.12769E-04
B6	Strong currents	3.98010E-05
B7	Strong winds	9.28690E-05
B8	Tide current	1.32670E-05
OFO	Other failures	
OFO1	Adrift	6.63350E-06
OFO2	Collide to the object	6.63350E-06
OFO3	Wrong light use	6.63350E-06
U	Unsafe action failures	
P	Personal errors	
P1	Failures related to decisions made	
P11	Ignoring the dangers	6.63350E-06
P12	Misjudgement of the situation	1.99005E-05
P13	Misrepresentation	6.63350E-06
P14	Misunderstanding/being misunderstood	1.32670E-05
P2	Perception failures	
P21	Carelessness	1.32670E-05
P22	Not accepting the risk/underestimated risk	6.63350E-06
P23	Not paying attention to dangers	6.63350E-06
P24	Paying no attention to warnings	6.63350E-06
P3	Ability errors	
P31	Inability to use devices effectively	6.63350E-06
P32	Lack of communication	1.99005E-05
P33	Lack of information	6.63350E-06
R	Rule violation failures	
R1	Errors caused by disobeying the rules	
R11	Disobeying instructions	6.63350E-06
R12	Disobeying the COLREG rules	2.12272E-04
R13	Insufficient lookout	7.29685E-05
R14	Non-implementation of bridge resource management	1.99005E-05

Table 3 Codes and probabilities of collision accidents (continued)

Code	*Description*	*Probability*
R2	Lack of fulfilment of duty	
R21	Non-implementation of bridge team management	1.32670E-05
R22	Not following the procedures	6.63350E-06
UO	Other failures	
UO1	Alcohol use	6.63350E-06
UO2	Lack of communication between bridge and engine room	6.63350E-06
UO3	Not knowing English/not having of proficiency in English language	6.63350E-06
UO4	Psychological situation	6.63350E-06
UO5	Using a mobile phone	6.63350E-06
UO6	Using different languages in communication	6.63350E-06

Table 4 Code and probabilities of grounding accidents

Code	*Description*	*Probability*
OF	Operational failures	
E	Equipment failures	
E1	Technical failures	
E11	Loss of electrical power/blackout	2.57442E-05
E12	Engine failure	1.80209E-04
E13	Loss of power	1.02977E-04
E14	Malfunction of ship stop system	1.28721E-05
E2	Hardware errors	
E21	Gear failure	1.28721E-05
E22	Air compressor failure	1.28721E-05
E23	Autopilot sensor failure	1.28721E-05
E24	Break of rope	1.28721E-05
E25	Coolant system not working	1.28721E-05
E26	Damage to the propeller	1.28721E-05
E27	Hydraulic hose malfunction	1.28721E-05
E28	Propeller failure	1.28721E-05
E29	Rudder failure	3.86163E-05
E210	Valve failure	1.28721E-05
E3	Errors due to lack of equipment	
E31	Lack of parts	1.28721E-05
E4	Other reasons	
E41	Lose control of the ship	1.28721E-05
E42	Loss of steering ability	1.28721E-05
E43	Ramp hitting to propeller	1.28721E-05
E44	Vessel does not respond the wheel	2.57442E-05

Table 4 Code and probabilities of grounding accidents (continued)

Code	*Description*	*Probability*
N	Navigation failures	
N1	Deviation from course	1.28721E-05
N2	Navigating close to coast	5.14883E-05
N3	Navigating on a different route	1.28721E-05
N4	Persistently continuing on the route	1.28721E-05
M	Manoeuvring failures	
M1	Being late for manoeuvring action	1.28721E-05
M2	Early start to manoeuvre	1.28721E-05
M3	Not doing avoidance manoeuvre	1.28721E-05
M4	Wrong manoeuvre	3.86163E-05
B	Bad weather conditions	
B1	Heavy rain	1.28721E-05
B2	Heavy weather conditions	3.34674E-04
B3	High waves	6.43604E-05
B4	Restricted visibility	6.43604E-05
B5	Storm	5.14883E-05
B6	Strong currents	3.86163E-05
B7	Strong winds	2.18825E-04
OFO	Other Errors	
OFO1	Bank effect	1.28721E-05
OFO2	Cargo shift	1.28721E-05
OFO3	Flooding	5.14883E-05
OFO4	Maintenance	1.28721E-05
U	Unsafe action failures	
P	Personal errors	
P1	Failures related to decisions made	
P11	Disobeying recommendations	1.28721E-05
P12	Misjudgement of the situation	1.28721E-05
P2	Perception failures	
P21	Carelessness	2.57442E-05
P22	Not paying attention to the signs and symbols on chart	1.28721E-05
P3	Ability errors	
P31	Captain’s unfamiliarity with port conditions	1.28721E-05
P32	Lack of education	1.28721E-05
P33	Not using navigational devices	2.57442E-05
P34	Not using the ECDIS chart at appropriate scale	1.28721E-05
R	Rule violation failures	
R1	Errors caused by disobeying the rules	

Table 4 Code and probabilities of grounding accidents (continued)

Code	*Description*	*Probability*
R11	Disobeying the COLREG rules	2.57442E-05
R12	Insufficient lookout	1.28721E-05
R2	Lack of fulfilment of duty	
R21	Non-implementation of bridge resource management	1.28721E-05
R22	Not following the procedures	1.28721E-05
UO	Other failures	
UO1	Absence of fuel	1.28721E-05
UO2	Alcohol use	2.57442E-05
UO3	Inability to command the ship	2.57442E-05
UO4	Inadequate bridge management	1.28721E-05
UO5	Insomnia/napping/sleeping	5.14883E-05
UO6	Leaving from the bridge	1.28721E-05
UO7	No one to command the ship	1.28721E-05
UO8	Routine work	1.28721E-05
UO9	The pilot's failure to inform	1.28721E-05
UO10	Tiredness/fatigue	1.28721E-05
UO11	Turning off alarms	2.57442E-05

Table 5 MCSs that causing collision accidents

Top 20			*Last 20*		
Rank	*Failures*	*Probability*	*Rank*	*Failures*	*Probability*
1	B5 and R12	2.39378E-02	949	E22, R21 and R22	5.83792E-10
2	B7 and R12	1.97135E-02	950	E23, R21 and R22	5.83792E-10
3	M6 and R12	9.85674E-03	951	E24, R21 and R22	5.83792E-10
4	B6 and R12	8.44864E-03	952	E25, R21 and R22	5.83792E-10
5	E12 and R12	8.44864E-03	953	E26, R21 and R22	5.83792E-10
6	B5 and R13	8.22862E-03	954	E27, R21 and R22	5.83792E-10
7	M1 and R12	7.04053E-03	955	E28, R21 and R22	5.83792E-10
8	M2 and R12	7.04053E-03	956	E29, R21 and R22	5.83792E-10
9	B7 and R13	6.77651E-03	957	E31, R21 and R22	5.83792E-10
10	B1 and R12	5.63242E-03	958	E32, R21 and R22	5.83792E-10
11	B3 and R12	5.63242E-03	959	E41, R21 and R22	5.83792E-10
12	E17 and R12	5.63242E-03	960	M3, R21 and R22	5.83792E-10
13	M6 and R13	3.38826E-03	961	M4, R21 and R22	5.83792E-10
14	B6 and R13	2.90422E-03	962	M5, R21 and R22	5.83792E-10
15	E12 and R13	2.90422E-03	963	N1, R21 and R22	5.83792E-10
16	B4 and R12	2.81621E-03	964	N2, R21 and R22	5.83792E-10
17	B8 and R12	2.81621E-03	965	N3, R21 and R22	5.83792E-10
18	E212 and R12	2.81621E-03	966	OFO1, R21 and R22	5.83792E-10
19	E213 and R12	2.81621E-03	967	OFO2, R21 and R22	5.83792E-10
20	M1 and R13	2.42018E-03	968	OFO3, R21 and R22	5.83792E-10

Figure 8 FT for grounding accidents (see online version for colours)

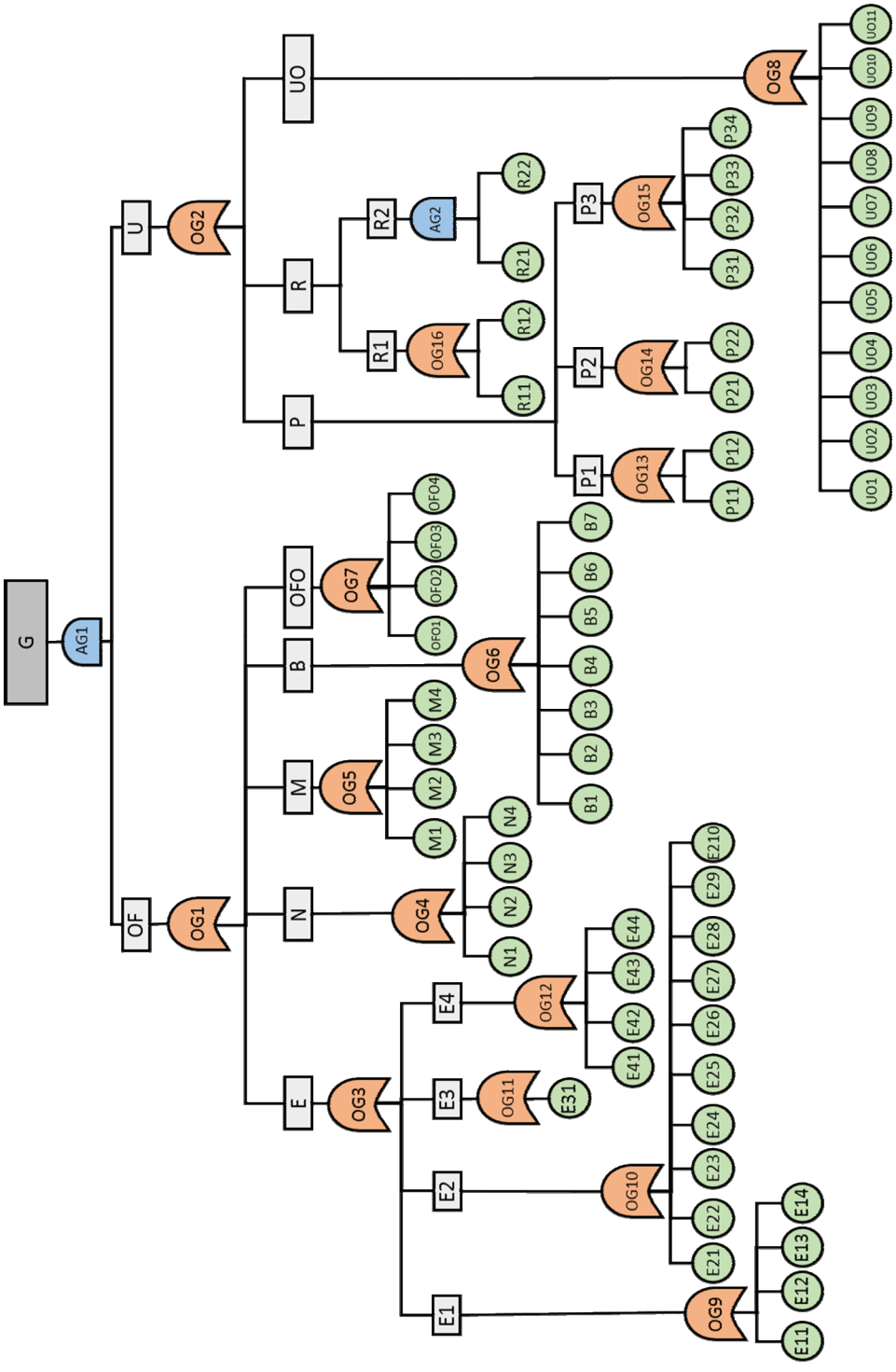
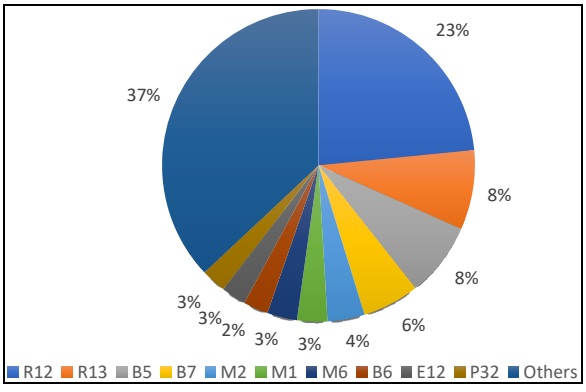


Table 6 Initial incident analysis for collision accidents

Event	*Failure contribution*	*Importance*
R12	1.55294E-01	23.45%
R13	5.45957E-02	8.24%
B5	5.09559E-02	7.69%
B7	3.88236E-02	5.86%
M2	2.54780E-02	3.85%
M1	2.06250E-02	3.12%
M6	2.06250E-02	3.12%
B6	1.69853E-02	2.57%
E12	1.69853E-02	2.57%
P32	1.69853E-02	2.57%

Figure 9 Contribution of initial events to the occurrence of collision accidents (see online version for colours)



Monte Carlo simulation is used in the OpenFTA program to determine and evaluate the impact of initial events on the occurrence of collision accidents. The distribution of errors is observed by increasing the number of tests performed with Monte Carlo simulation. The reasons that contributed to the accident by 2.57% and above from the data obtained are given in Table 6. Figure 9 is created to see the contribution of the reasons given in Table 6 and other causes (reasons less than 2.57%) to the accident.

When the contribution of initial events to the formation of collision accidents is examined, the five root causes with the highest contribution are R12 (disobeying the COLREG rules) with 23.45%, R13 (insufficient lookout) with 8.24%, B5 (storm) with 7.69%, It has been determined as B7 (strong winds) with 86% and M2 (narrow manoeuvre area) with 3.85%.

As a result of the analysis made with OpenFTA software, MCSs of grounding accidents have been determined. As a result of the analysis, 836 MCSs have been found. Table 7 presents the MCSs and probabilities that cause grounding accidents. Since the number of MCSs is high, a total of 40 MCSs, 20 from the beginning and the end are given in Table 7. In addition, the probabilities of the MCSs are listed in Table 7 in order from largest to smallest.

Table 7 MCSs to cause grounding accidents

Top 20			*Last 20*		
Rank	*Failures*	*Probability*	*Rank*	*Failures*	*Probability*
1	B2 and UO5	1.72318E-02	817	E22, R21 and R22	2.13278E-09
2	B7 and UO5	1.12670E-02	818	E23, R21 and R22	2.13278E-09
3	E12 and UO5	9.27867E-03	819	E24, R21 and R22	2.13278E-09
4	B2 and P21	8.61591E-03	820	E25, R21 and R22	2.13278E-09
5	B2 and P33	8.61591E-03	821	E26, R21 and R22	2.13278E-09
6	B2 and R11	8.61591E-03	822	E27, R21 and R22	2.13278E-09
7	B2 and UO11	8.61591E-03	823	E28, R21 and R22	2.13278E-09
8	B2 and UO3	8.61591E-03	824	E31, R21 and R22	2.13278E-09
9	B2 and UO2	8.61591E-03	825	E41, R21 and R22	2.13278E-09
10	B7 and P21	5.63348E-03	826	E42, R21 and R22	2.13278E-09
11	B7 and P33	5.63348E-03	827	E43, R21 and R22	2.13278E-09
12	B7 and R11	5.63348E-03	828	M1, R21 and R22	2.13278E-09
13	B7 and UO11	5.63348E-03	829	M2, R21 and R22	2.13278E-09
14	B7 and UO3	5.63348E-03	830	M3, R21 and R22	2.13278E-09
15	B7 and UO2	5.63348E-03	831	N1, R21 and R22	2.13278E-09
16	E13 and UO5	5.30210E-03	832	N3, R21 and R22	2.13278E-09
17	E12 and P21	4.63934E-03	833	N4, R21 and R22	2.13278E-09
18	E12 and P33	4.63934E-03	834	OFO1, R21 and R22	2.13278E-09
19	E12 and R11	4.63934E-03	835	OFO2, R21 and R22	2.13278E-09
20	E12 and UO11	4.63934E-03	836	OFO4, R21 and R22	2.13278E-09

Table 8 Initial event analysis for grounding accidents

Event	*Failure contribution*	*Importance*
B2	1.28394E-01	10.49%
UO5	8.22521E-02	6.72%
E12	7.02152E-02	5.74%
B7	6.41968E-02	5.25%
E13	5.01537E-02	4.10%
P33	4.41353E-02	3.61%
UO11	4.41353E-02	3.61%
UO2	4.21291E-02	3.45%
UO3	4.01230E-02	3.28%
P32	3.20984E-02	2.63%

Monte Carlo simulation is used in the OpenFTA program to determine and evaluate the impact of initial events on the occurrence of grounding accidents. The distribution of errors is observed by increasing the number of tests performed with Monte Carlo simulation. The reasons that contributed to the accident by 2.63% and above from the data obtained are given in Table 8. Figure 10 is created to see the contribution of the reasons given in Table 8 and other causes (reasons less than 2.63%) to the accident.

Table 9 Sensitivity analysis results for collision accidents

Operational failures						*Unsafe action failures*					
10%			*–10%*			*10%*			*–10%*		
Event	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*
R12	1.70E-01	43.83%	R12	1.68E-01	47.29%	R12	1.43E-01	50.62%	R12	1.68E-01	48.84%
R13	7.82E-02	20.13%	R13	5.02E-02	14.08%	R13	3.49E-02	12.35%	R13	5.70E-02	16.61%
B7	4.92E-02	12.66%	B5	4.12E-02	11.55%	B7	3.38E-02	11.93%	B5	4.90E-02	14.29%
B5	4.54E-02	11.69%	B7	3.60E-02	10.11%	B5	2.91E-02	10.29%	B7	2.85E-02	8.31%
M6	3.66E-02	9.42%	M6	3.09E-02	8.66%	M6	2.45E-02	8.64%	M6	2.85E-02	8.31%
E12	2.52E-02	6.49%	B6	2.57E-02	7.22%	B6	2.21E-02	7.82%	P32	2.39E-02	6.98%
P12	2.02E-02	5.19%	E12	2.19E-02	6.14%	M2	1.98E-02	7.00%	B6	2.05E-02	5.98%
P32	2.02E-02	5.19%	P12	2.19E-02	6.14%	R14	1.86E-02	6.58%	E12	2.05E-02	5.98%
B6	1.77E-02	4.55%	M2	1.80E-02	5.05%	M1	1.51E-02	5.35%	E17	1.94E-02	5.65%
E17	1.64E-02	4.22%	E17	1.54E-02	4.33%	P12	1.51E-02	5.35%	M2	1.60E-02	4.65%
R14	1.39E-02	3.57%	M1	1.29E-02	3.61%	E17	1.40E-02	4.94%	B1	1.37E-02	3.99%
B1	1.14E-02	2.92%	P14	1.29E-02	3.61%	B1	9.32E-03	3.29%	M1	1.37E-02	3.99%
M1	1.14E-02	2.92%	R14	1.29E-02	3.61%	E12	9.32E-03	3.29%	P12	1.25E-02	3.65%
M2	1.14E-02	2.92%	B3	1.16E-02	3.25%	E212	8.15E-03	2.88%	R14	1.14E-02	3.32%
B3	1.01E-02	2.60%	B4	1.16E-02	3.25%	P21	8.15E-03	2.88%	P14	9.12E-03	2.66%
E212	1.01E-02	2.60%	E213	1.16E-02	3.25%	P32	8.15E-03	2.88%	P21	9.12E-03	2.66%
P14	1.01E-02	2.60%	P21	1.16E-02	3.25%	B4	6.99E-03	2.47%	B2	7.98E-03	2.33%
B4	8.83E-03	2.27%	B1	1.03E-02	2.89%	E213	6.99E-03	2.47%	B3	7.98E-03	2.33%
P21	8.83E-03	2.27%	P32	1.03E-02	2.89%	OFO3	5.82E-03	2.06%	M3	7.98E-03	2.33%
UO4	8.83E-03	2.27%	E212	9.00E-03	2.53%	P11	5.82E-03	2.06%	N3	7.98E-03	2.33%
P13	7.57E-03	1.95%	OFO1	9.00E-03	2.53%	P31	5.82E-03	2.06%	B8	6.84E-03	1.99%
R11	7.57E-03	1.95%	B8	7.72E-03	2.17%	UO5	5.82E-03	2.06%	E212	6.84E-03	1.99%
E18	6.31E-03	1.62%	P11	7.72E-03	2.17%	E11	5.82E-03	2.06%	E32	6.84E-03	1.99%
E210	6.31E-03	1.62%	E31	6.43E-03	1.81%	B3	4.66E-03	1.65%	P33	6.84E-03	1.99%

Table 9 Sensitivity analysis results for collision accidents (continued)

Operational failures						*Unsafe action failures*					
10%			*–10%*			*10%*			*–10%*		
Event	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*
E32	6.31E-03	1.62%	M5	6.43E-03	1.81%	E18	4.66E-03	1.65%	UO2	6.84E-03	1.99%
E41	6.31E-03	1.62%	P23	6.43E-03	1.81%	P13	4.66E-03	1.65%	E22	5.70E-03	1.66%
M3	6.31E-03	1.62%	P24	6.43E-03	1.81%	P14	4.66E-03	1.65%	M5	5.70E-03	1.66%
N1	6.31E-03	1.62%	P31	6.43E-03	1.81%	UO3	4.66E-03	1.65%	OFO1	5.70E-03	1.66%
OFO3	6.31E-03	1.62%	R11	6.43E-03	1.81%	B2	3.49E-03	1.23%	B4	4.56E-03	1.33%
P22	6.31E-03	1.62%	UO1	6.43E-03	1.81%	B8	3.49E-03	1.23%	E31	4.56E-03	1.33%
UO1	6.31E-03	1.62%	UO3	6.43E-03	1.81%	E14	3.49E-03	1.23%	E41	4.56E-03	1.33%
E11	6.31E-03	1.62%	UO5	6.43E-03	1.81%	E210	3.49E-03	1.23%	N1	4.56E-03	1.33%
B8	5.05E-03	1.30%	E15	5.14E-03	1.44%	E26	3.49E-03	1.23%	N2	4.56E-03	1.33%
E13	5.05E-03	1.30%	E16	5.14E-03	1.44%	E27	3.49E-03	1.23%	P11	4.56E-03	1.33%
E22	5.05E-03	1.30%	E210	5.14E-03	1.44%	E29	3.49E-03	1.23%	P24	4.56E-03	1.33%
E24	5.05E-03	1.30%	E25	5.14E-03	1.44%	M3	3.49E-03	1.23%	UO4	4.56E-03	1.33%
E25	5.05E-03	1.30%	P22	5.14E-03	1.44%	M5	3.49E-03	1.23%	UO5	4.56E-03	1.33%
M5	5.05E-03	1.30%	B2	3.86E-03	1.08%	OFO2	3.49E-03	1.23%	E211	3.42E-03	1.00%
N2	5.05E-03	1.30%	E23	3.86E-03	1.08%	UO1	3.49E-03	1.23%	E27	3.42E-03	1.00%
P31	5.05E-03	1.30%	E32	3.86E-03	1.08%	UO2	3.49E-03	1.23%	OFO2	3.42E-03	1.00%
UO2	5.05E-03	1.30%	E41	3.86E-03	1.08%	UO6	3.49E-03	1.23%	P23	3.42E-03	1.00%
UO3	5.05E-03	1.30%	M4	3.86E-03	1.08%	E16	2.33E-03	0.82%	R11	3.42E-03	1.00%
B2	3.78E-03	0.97%	P13	3.86E-03	1.08%	E22	2.33E-03	0.82%	UO1	3.42E-03	1.00%
E15	3.78E-03	0.97%	UO2	3.86E-03	1.08%	E23	2.33E-03	0.82%	UO6	3.42E-03	1.00%
E213	3.78E-03	0.97%	E13	2.57E-03	0.72%	E31	2.33E-03	0.82%	E11	3.42E-03	1.00%
E26	3.78E-03	0.97%	E18	2.57E-03	0.72%	M4	2.33E-03	0.82%	E13	2.28E-03	0.66%
E27	3.78E-03	0.97%	E211	2.57E-03	0.72%	OFO1	2.33E-03	0.82%	E14	2.28E-03	0.66%
E31	3.78E-03	0.97%	E27	2.57E-03	0.72%	P22	2.33E-03	0.82%	E15	2.28E-03	0.66%

Table 9 Sensitivity analysis results for collision accidents (continued)

Operational failures						*Unsafe action failures*					
10%			*−10%*			*10%*			*−10%*		
Event	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*
N3	3.78E-03	0.97%	E28	2.57E-03	0.72%	P23	2.33E-03	0.82%	E18	2.28E-03	0.66%
OFO2	3.78E-03	0.97%	N3	2.57E-03	0.72%	P33	2.33E-03	0.82%	E210	2.28E-03	0.66%
P11	3.78E-03	0.97%	OFO2	2.57E-03	0.72%	R11	2.33E-03	0.82%	E23	2.28E-03	0.66%
P24	3.78E-03	0.97%	OFO3	2.57E-03	0.72%	UO4	2.33E-03	0.82%	E25	2.28E-03	0.66%
P33	3.78E-03	0.97%	E11	2.57E-03	0.72%	E13	1.16E-03	0.41%	E26	2.28E-03	0.66%
E14	2.52E-03	0.65%	E21	1.29E-03	0.36%	E15	1.16E-03	0.41%	E29	2.28E-03	0.66%
E21	2.52E-03	0.65%	E22	1.29E-03	0.36%	E21	1.16E-03	0.41%	M4	2.28E-03	0.66%
E211	2.52E-03	0.65%	E26	1.29E-03	0.36%	E211	1.16E-03	0.41%	P13	2.28E-03	0.66%
E29	2.52E-03	0.65%	M3	1.29E-03	0.36%	E24	1.16E-03	0.41%	P22	2.28E-03	0.66%
M4	2.52E-03	0.65%	N1	1.29E-03	0.36%	E25	1.16E-03	0.41%	UO3	2.28E-03	0.66%
OFO1	2.52E-03	0.65%	N2	1.29E-03	0.36%	E28	1.16E-03	0.41%	E21	1.14E-03	0.33%
UO6	2.52E-03	0.65%	P33	1.29E-03	0.36%	E32	1.16E-03	0.41%	E213	1.14E-03	0.33%
E16	1.26E-03	0.32%	UO4	1.29E-03	0.36%	E41	1.16E-03	0.41%	E28	1.14E-03	0.33%
E23	1.26E-03	0.32%	E14	0.00E+00	0.00%	N1	1.16E-03	0.41%	OFO3	1.14E-03	0.33%
E28	1.26E-03	0.32%	E24	0.00E+00	0.00%	N2	1.16E-03	0.41%	E16	0.00E+00	0.00%
UO5	1.26E-03	0.32%	E29	0.00E+00	0.00%	N3	1.16E-03	0.41%	E24	0.00E+00	0.00%
P23	0.00E+00	0.00%	R21	0.00E+00	0.00%	P24	1.16E-03	0.41%	P31	0.00E+00	0.00%
R21	0.00E+00	0.00%	R22	0.00E+00	0.00%	R21	0.00E+00	0.00%	R21	0.00E+00	0.00%
R22	0.00E+00	0.00%	UO6	0.00E+00	0.00%	R22	0.00E+00	0.00%	R22	0.00E+00	0.00%

Table 10 Sensitivity analysis results for grounding accidents

Operational failures						*Unsafe action failures*					
10%			*–10%*			*10%*			*–10%*		
Event	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*
B2	1.29E-01	20.52%	B2	1.65E-01	23.60%	B2	1.20E-01	20.96%	B2	1.03E-01	19.05%
B7	9.21E-02	14.66%	UO5	9.74E-02	13.98%	UO5	8.84E-02	15.46%	UO5	7.57E-02	13.95%
UO5	7.78E-02	12.38%	B7	8.88E-02	12.73%	B7	7.47E-02	13.06%	B7	7.20E-02	13.27%
E12	6.14E-02	9.77%	E12	5.63E-02	8.07%	E12	5.90E-02	10.31%	E12	5.73E-02	10.54%
P33	4.91E-02	7.82%	UO2	5.20E-02	7.45%	P21	4.32E-02	7.56%	R11	4.43E-02	8.16%
P21	4.91E-02	7.82%	E13	4.33E-02	6.21%	UO11	4.32E-02	7.56%	P21	4.06E-02	7.48%
UO3	4.50E-02	7.17%	P21	4.33E-02	6.21%	UO7	4.13E-02	7.22%	E13	3.88E-02	7.14%
E13	4.09E-02	6.51%	P33	4.33E-02	6.21%	UO3	3.54E-02	6.19%	UO11	3.88E-02	7.14%
UO11	3.69E-02	5.86%	UO3	4.11E-02	5.90%	B3	3.14E-02	5.50%	P33	3.32E-02	6.12%
P34	3.48E-02	5.54%	UO11	3.68E-02	5.28%	UO2	3.14E-02	5.50%	UO3	3.32E-02	6.12%
R11	3.28E-02	5.21%	B3	3.46E-02	4.97%	E13	2.75E-02	4.81%	B4	2.95E-02	5.44%
N2	3.07E-02	4.89%	B6	3.46E-02	4.97%	P12	2.75E-02	4.81%	UO2	2.95E-02	5.44%
UO1	2.87E-02	4.56%	P32	3.46E-02	4.97%	R11	2.75E-02	4.81%	M4	2.40E-02	4.42%
UO2	2.87E-02	4.56%	UO8	3.46E-02	4.97%	B6	2.55E-02	4.47%	P11	2.40E-02	4.42%
UO6	2.87E-02	4.56%	B5	3.25E-02	4.66%	B4	2.36E-02	4.12%	P12	2.22E-02	4.08%
R12	2.46E-02	3.91%	R11	3.25E-02	4.66%	P33	2.36E-02	4.12%	P31	2.22E-02	4.08%
UO10	2.46E-02	3.91%	UO7	3.25E-02	4.66%	B5	2.16E-02	3.78%	P22	2.03E-02	3.74%
B4	2.25E-02	3.58%	UO4	3.03E-02	4.35%	M4	2.16E-02	3.78%	UO4	2.03E-02	3.74%
UO8	2.25E-02	3.58%	UO1	2.82E-02	4.04%	OFO3	2.16E-02	3.78%	UO6	2.03E-02	3.74%
P11	2.05E-02	3.26%	UO9	2.82E-02	4.04%	UO4	2.16E-02	3.78%	UO9	2.03E-02	3.74%
P12	2.05E-02	3.26%	OFO3	2.60E-02	3.73%	P11	1.97E-02	3.44%	B5	1.85E-02	3.40%
P31	2.05E-02	3.26%	P12	2.60E-02	3.73%	P22	1.97E-02	3.44%	B6	1.85E-02	3.40%
UO9	2.05E-02	3.26%	P22	2.60E-02	3.73%	UO10	1.97E-02	3.44%	P34	1.85E-02	3.40%
B3	1.84E-02	2.93%	UO10	2.60E-02	3.73%	P31	1.77E-02	3.09%	R12	1.85E-02	3.40%

Table 10 Sensitivity analysis results for grounding accidents (continued)

Operational failures						*Unsafe action failures*					
10%			*–10%*			*10%*			*–10%*		
Event	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*
P32	1.84E-02	2.93%	M4	2.38E-02	3.42%	P34	1.77E-02	3.09%	B3	1.66E-02	3.06%
UO4	1.84E-02	2.93%	N2	2.17E-02	3.11%	R12	1.77E-02	3.09%	UO7	1.48E-02	2.72%
B6	1.64E-02	2.61%	R12	2.17E-02	3.11%	UO8	1.77E-02	3.09%	E29	1.29E-02	2.38%
OFO3	1.64E-02	2.61%	P34	1.95E-02	2.80%	UO1	1.57E-02	2.75%	N2	1.29E-02	2.38%
M4	1.43E-02	2.28%	UO6	1.95E-02	2.80%	UO6	1.57E-02	2.75%	UO1	1.29E-02	2.38%
P22	1.43E-02	2.28%	B4	1.73E-02	2.48%	UO9	1.57E-02	2.75%	UO10	1.29E-02	2.38%
E29	1.23E-02	1.95%	P31	1.73E-02	2.48%	E44	1.38E-02	2.41%	OFO3	1.11E-02	2.04%
E31	1.23E-02	1.95%	OFO4	1.52E-02	2.17%	N2	1.18E-02	2.06%	OFO4	1.11E-02	2.04%
UO7	1.23E-02	1.95%	E29	1.30E-02	1.86%	P32	1.18E-02	2.06%	P32	1.11E-02	2.04%
B5	1.02E-02	1.63%	E44	1.30E-02	1.86%	M1	9.83E-03	1.72%	E23	9.23E-03	1.70%
E210	1.02E-02	1.63%	M1	1.08E-02	1.55%	M3	9.83E-03	1.72%	E42	9.23E-03	1.70%
E23	1.02E-02	1.63%	E11	1.08E-02	1.55%	E11	9.83E-03	1.72%	E44	9.23E-03	1.70%
E44	1.02E-02	1.63%	E210	8.66E-03	1.24%	E21	7.86E-03	1.37%	UO8	9.23E-03	1.70%
OFO4	1.02E-02	1.63%	E24	6.50E-03	0.93%	E25	7.86E-03	1.37%	E11	9.23E-03	1.70%
B1	8.19E-03	1.30%	E25	6.50E-03	0.93%	E29	7.86E-03	1.37%	M1	7.39E-03	1.36%
E14	8.19E-03	1.30%	E28	6.50E-03	0.93%	E14	5.90E-03	1.03%	N1	7.39E-03	1.36%
E24	8.19E-03	1.30%	OFO1	6.50E-03	0.93%	E210	5.90E-03	1.03%	E24	5.54E-03	1.02%
E26	8.19E-03	1.30%	P11	6.50E-03	0.93%	E28	5.90E-03	1.03%	E28	5.54E-03	1.02%
M1	8.19E-03	1.30%	E14	4.33E-03	0.62%	E31	5.90E-03	1.03%	M3	5.54E-03	1.02%
E22	6.14E-03	0.98%	E21	4.33E-03	0.62%	OFO2	5.90E-03	1.03%	B1	3.69E-03	0.68%
E25	6.14E-03	0.98%	E22	4.33E-03	0.62%	E22	3.93E-03	0.69%	E14	3.69E-03	0.68%
E41	6.14E-03	0.98%	E26	4.33E-03	0.62%	E26	3.93E-03	0.69%	E21	3.69E-03	0.68%
E42	6.14E-03	0.98%	E27	4.33E-03	0.62%	E41	3.93E-03	0.69%	E210	3.69E-03	0.68%
N3	6.14E-03	0.98%	E31	4.33E-03	0.62%	M2	3.93E-03	0.69%	E22	3.69E-03	0.68%

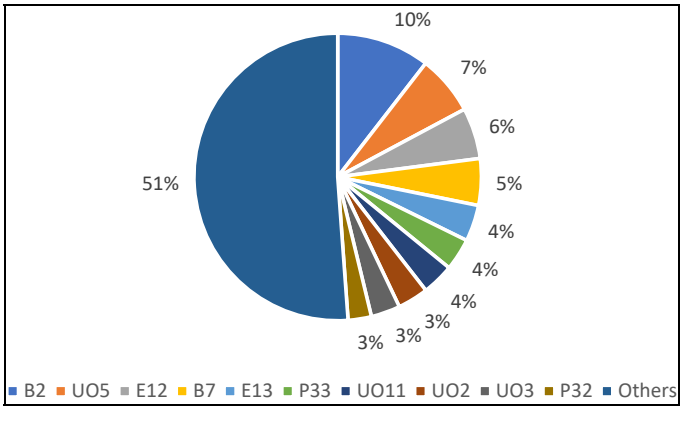
Table 10 Sensitivity analysis results for grounding accidents (continued)

Operational failures						*Unsafe action failures*					
10%			*−10%*			*10%*			*−10%*		
Event	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*	*Event*	*Failure contribution*	*Importance*
OFO1	6.14E-03	0.98%	E41	4.33E-03	0.62%	N1	3.93E-03	0.69%	E26	3.69E-03	0.68%
E21	4.09E-03	0.65%	M3	4.33E-03	0.62%	N3	3.93E-03	0.69%	E41	3.69E-03	0.68%
E27	4.09E-03	0.65%	N4	4.33E-03	0.62%	B1	1.97E-03	0.34%	M2	3.69E-03	0.68%
E28	4.09E-03	0.65%	OFO2	4.33E-03	0.62%	E23	1.97E-03	0.34%	N4	3.69E-03	0.68%
M2	4.09E-03	0.65%	B1	2.17E-03	0.31%	E24	1.97E-03	0.34%	OFO1	3.69E-03	0.68%
M3	4.09E-03	0.65%	E23	2.17E-03	0.31%	E27	1.97E-03	0.34%	OFO2	3.69E-03	0.68%
N1	4.09E-03	0.65%	E43	2.17E-03	0.31%	E43	1.97E-03	0.34%	E25	1.85E-03	0.34%
N4	4.09E-03	0.65%	M2	2.17E-03	0.31%	OFO1	1.97E-03	0.34%	E27	1.85E-03	0.34%
E11	4.09E-03	0.65%	N1	2.17E-03	0.31%	OFO4	1.97E-03	0.34%	E31	1.85E-03	0.34%
E43	0.00E+00	0.00%	N3	2.17E-03	0.31%	E42	0.00E+00	0.00%	E43	1.85E-03	0.34%
OFO2	0.00E+00	0.00%	E42	0.00E+00	0.00%	N4	0.00E+00	0.00%	N3	0.00E+00	0.00%
R21	0.00E+00	0.00%	R21	0.00E+00	0.00%	R21	0.00E+00	0.00%	R21	0.00E+00	0.00%
R22	0.00E+00	0.00%	R22	0.00E+00	0.00%	R22	0.00E+00	0.00%	R22	0.00E+00	0.00%

Table 11 The prevention criteria for collision and grounding

Collision incidents			
Incident causes		*Prevention criteria*	
R12	Disobeying the COLREG rules	R12a	Education
		R12b	Awareness
		R12c	Practice
R13	Insufficient lookout	R13a	Availability of watchman
		R13b	Experience
		R13c	Adequate rest
B5	Storm	B5a	Weather tracking
		B5b	Taking appropriate precautions
		B5c	Ship condition
		B5d	Experienced officer
Grounding incidents			
Incident causes		*Prevention criteria*	
B2	Heavy weather conditions	B2a	Weather tracking
		B2b	Taking appropriate precautions
		B2c	Ship condition
		B2d	Experienced officer
UO5	Insufficient lookout	UO5a	Availability of watchman
		UO5b	Experience
		UO5c	Adequate rest
E12	Engine failures	E12a	Maintenance
		E12b	Age of the ship
		E12c	Experience of maintenance personnel

Figure 10 Contribution of initial events to the occurrence of grounding accidents (see online version for colours)



When the contribution of initial events to the occurrence of grounding accidents is examined, the five root causes with the highest contribution are B2 (heavy weather conditions) with 10.49%, UO5 (insufficient lookout) with 6.72%, E12 (engine failure) with 5.74%, It is determined as B7 (strong winds) with 25%, E13 (loss of power) with 4.10%.

4.2 Sensitivity analysis

Sensitivity analysis of FTs belonging to collision and grounding accidents is performed separately. While performing the sensitivity analysis, the probability values of the initial events in the collision and grounding FTs are separately increased or decreased by 10% and analysed again with the OpenFTA program (Uğurlu, 2011; Tuncel, 2020). According to the results of the analysis, the changes in the contribution values and importance levels of the initial events are examined. As a result of the data obtained, Table 9 for collision accidents and Table 10 for grounding accidents are created. Table 9 is obtained as a result of increasing and decreasing the probability values under the main heading of operational errors and unsafe motion errors in the FT of collision accidents by 10% separately. As a result of the sensitivity analysis committed in Table 9, the contribution margins of the main causes and the changes in the degree of significance are observed.

Table 10 is obtained as a result of increasing and decreasing the probability values under the main heading of operational errors and unsafe movement errors in the FT of grounding accidents by 10% separately. As a result of the sensitivity analysis, Table 10 shows the contribution margins of the main causes and the changes in the degree of significance.

4.3 FUCOM

The decision criteria used for this study are determined by considering a comprehensive literature review and three expert opinions for the suggestions to prevent accident causes with the highest value obtained as a result of FTA. The determined criteria are given in Table 11. The aim of including more than one expert in the decision process is to minimise conflicts of interest and personal prejudices (Ecer, 2021). All of the selected experts are experts in the maritime field, have sufficient experience and are academicians.

Table 12 Ranking of the criteria according to expert opinions

Accident type	*Accident causes*	*Ranking*		
		Expert 1	*Expert 2*	*Expert 3*
Collision	R12	R12a > R12c > R12b	R12b > R12a > R12c	R12b > R12a > R12c
	R13	R13a > R13c > R13b	R13a > R13b > R13c	R13a > R13b > R13c
	B5	B5a > B5c > B5b > B5d	B5d > B5c > B5b > B5a	B5d > B5b > B5c > B5a
Grounding	B2	B2a > B2c > B2b > B2d	B2b > B2c > B2a > B2d	B2d > B2a > B2b > B2c
	UO5	UO5a > UO5c > UO5b	UO5c > UO5a > UO5b	UO5a >UO5b > UO5c
	E12	E12a > E12b > E12c	E12a > E12c > E12b	E12b > E12c > E12a

Note: *'>' represents the 'is more important than'.

With the FUCOM method, the importance weights of the criteria are found as follows:

Step 1 The experts first ranked the decision criteria according to their importance level based on their personal thoughts and experiences. The rank determined by the experts is given in Table 12.

Step 2 After ranking, the experts compared the criteria based on a scale of 1–9 (1: lowest, 9: highest). Experts have always made comparisons according to the most important criteria. The comparisons made by the experts for the criteria are given in Table 13.

Table 13 Scoring of the criteria by experts

Accident type	*Criteria*	*Expert 1*	*Expert 2*	*Expert 3*
Collision	R12a	1	3	3
	R12b	5	1	1
	R12c	3	4	4
	R13a	1	1	1
	R13b	9	3	3
	R13c	5	4	6
	B5a	1	5	7
	B5b	5	4	3
	B5c	3	3	5
	B5d	9	1	1
Grounding	B2a	1	4	2
	B2b	5	1	4
	B2c	3	3	9
	B2d	9	5	1
	UO5a	1	3	1
	UO5b	7	4	3
	UO5c	3	1	4
	E12a	1	1	3
	E12b	3	4	1
	E12c	7	5	2

Step 3 In the last step, two conditions are checked that must be met to obtain the optimum values.

The applications specified in all steps are entered into the software and the final weight values are obtained. The values are given in Table 14.

4.4 ETA

After analysing each tree, ETA is used to prevent or reduce the three most likely accident causes. The decision or action points determined in the event tree are determined according to expert opinions and the event tree is created by calculating their weights with the FUCOM method. The generated tree and probability values are analysed with LOGAN FTA software.

Table 14 Local weights of criteria

Accident type	*Accident cause*	*Prevention criteria*	*Expert 1*	*Expert 2*	*Expert 3*	*Local weight*
Collision	R12	R12a	0.652	0.211	0.211	0.358
		R12b	0.130	0.632	0.632	0.465
		R12c	0.217	0.158	0.158	0.178
	R13	R13a	0.763	0.763	0.667	0.731
		R13b	0.153	0.153	0.222	0.176
		R13c	0.085	0.085	0.111	0.094
	B5	B5a	0.608	0.112	0.085	0.268
		B5b	0.122	0.140	0.199	0.154
		B5c	0.203	0.187	0.119	0.170
		B5d	0.068	0.561	0.597	0.408
Grounding	B2	B2a	0.608	0.140	0.269	0.339
		B2b	0.122	0.561	0.134	0.272
		B2c	0.203	0.187	0.060	0.150
		B2d	0.068	0.112	0.537	0.239
	UO5	UO5a	0.677	0.211	0.632	0.507
		UO5b	0.097	0.158	0.211	0.155
		UO5c	0.226	0.632	0.158	0.338
	E12	E12a	0.677	0.690	0.182	0.516
		E12b	0.226	0.138	0.545	0.303
		E12c	0.097	0.172	0.273	0.181

According to expert opinions, the decision or actions are determined to prevent or reduce the causes of collision and grounding accidents. Event trees are created and analysed according to the decision points. The event trees and analysis results obtained for the most important *R12 disobeying the COLREG rules*, *UO5 insufficient lookout*, *B5 storm* are given in Figures 11 to 13.

The event trees and analysis results obtained for *B2 heavy weather conditions*, *UO5 insufficient lookout*, *E12 engine failure*, which have the highest degree of importance among the causes of grounding accidents, are given in Figure 14 to 16.

5 Discussion

Most of the transportation is carried out by sea (Ece et al., 2020). The number and type of accidents at sea are also quite high. Among these accident types related to navigation, collision, and grounding accidents are examined in this study.

The main causes and severity of the accidents were determined by FTA. The ETA method was used to give recommendations to prevent the six most important causes. However, there were difficulties in determining the probabilities of the precautionary points in the ETA method because there does not exist precautionary points in the examined accidents. A new method has been explored to solve this problem. In the study, it is found that the FUCOM method would be appropriate. The FUCOM method is a new method and an innovative model for creating a hybrid method that has not been used before in the maritime field.

Figure 11 Event tree for non-compliance with the COLREG rules

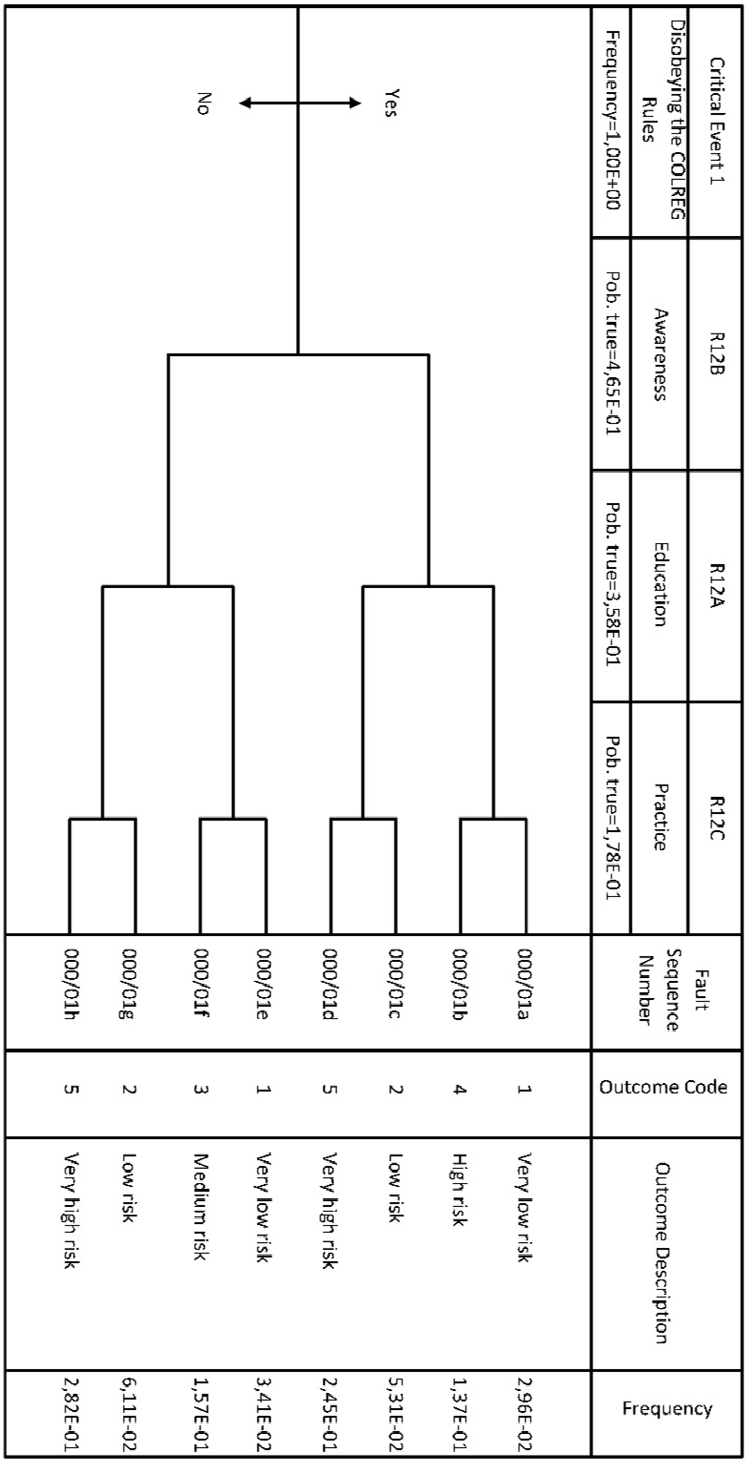


Figure 12 Event tree for UO5 insufficient lookout

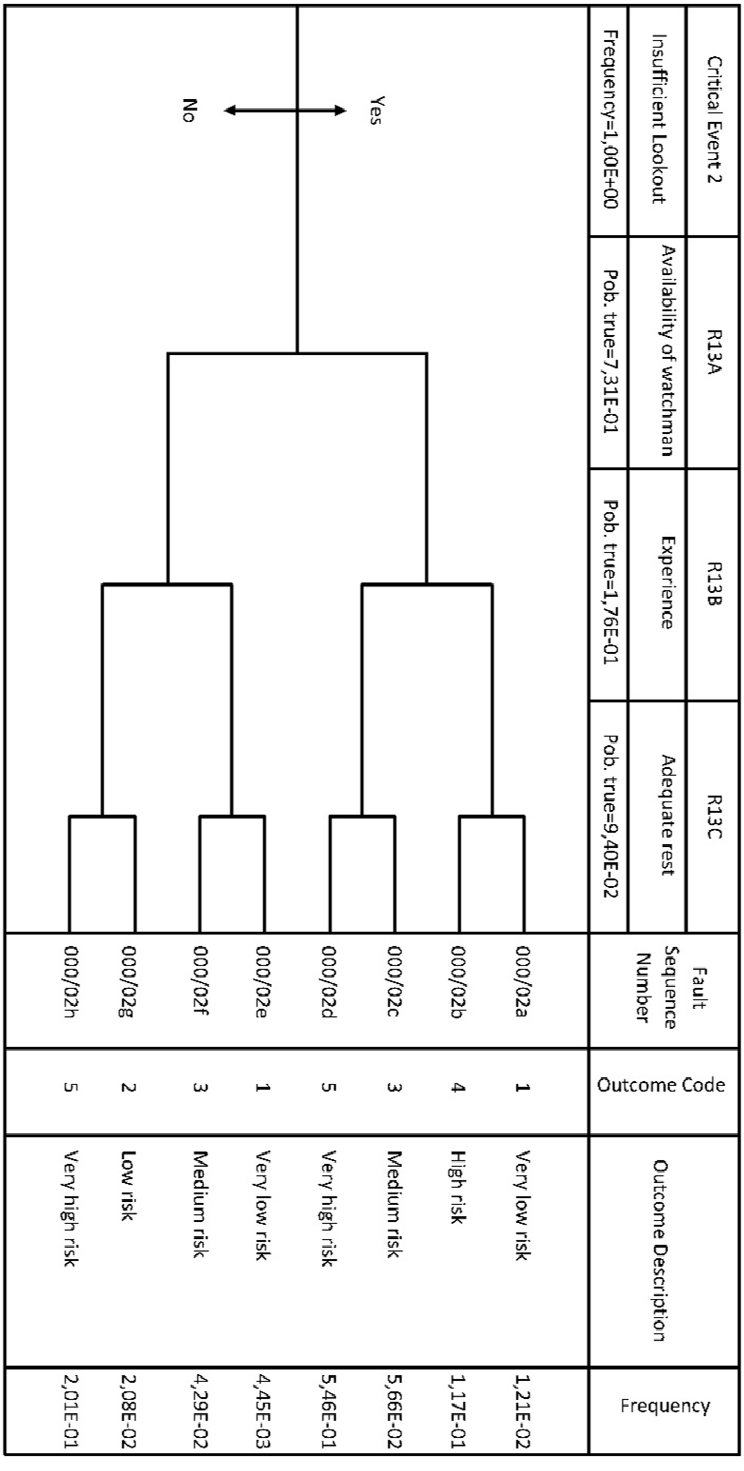


Figure 13 Event tree for B5 storm

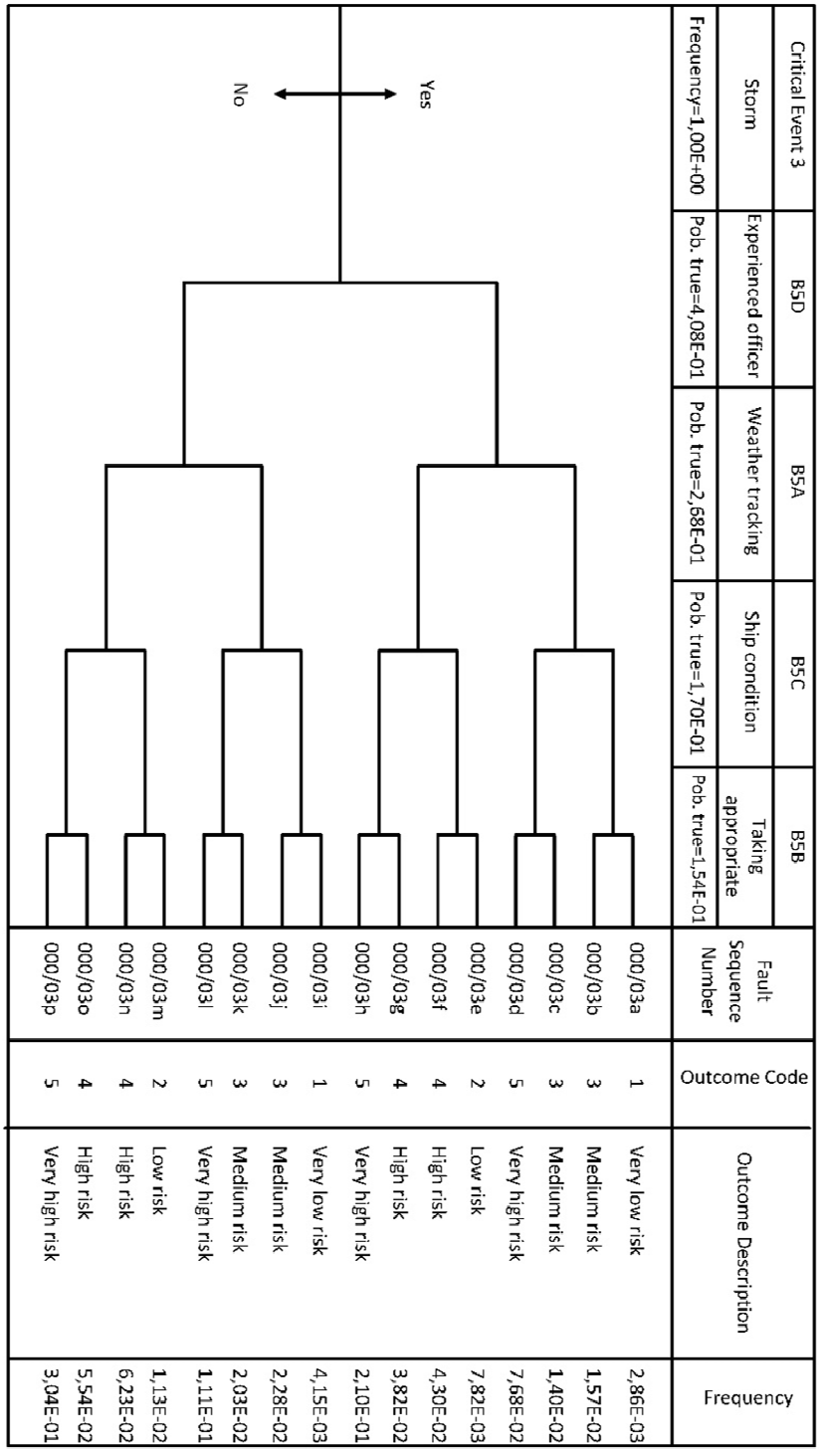


Figure 14 Event tree for B2 heavy weather conditions

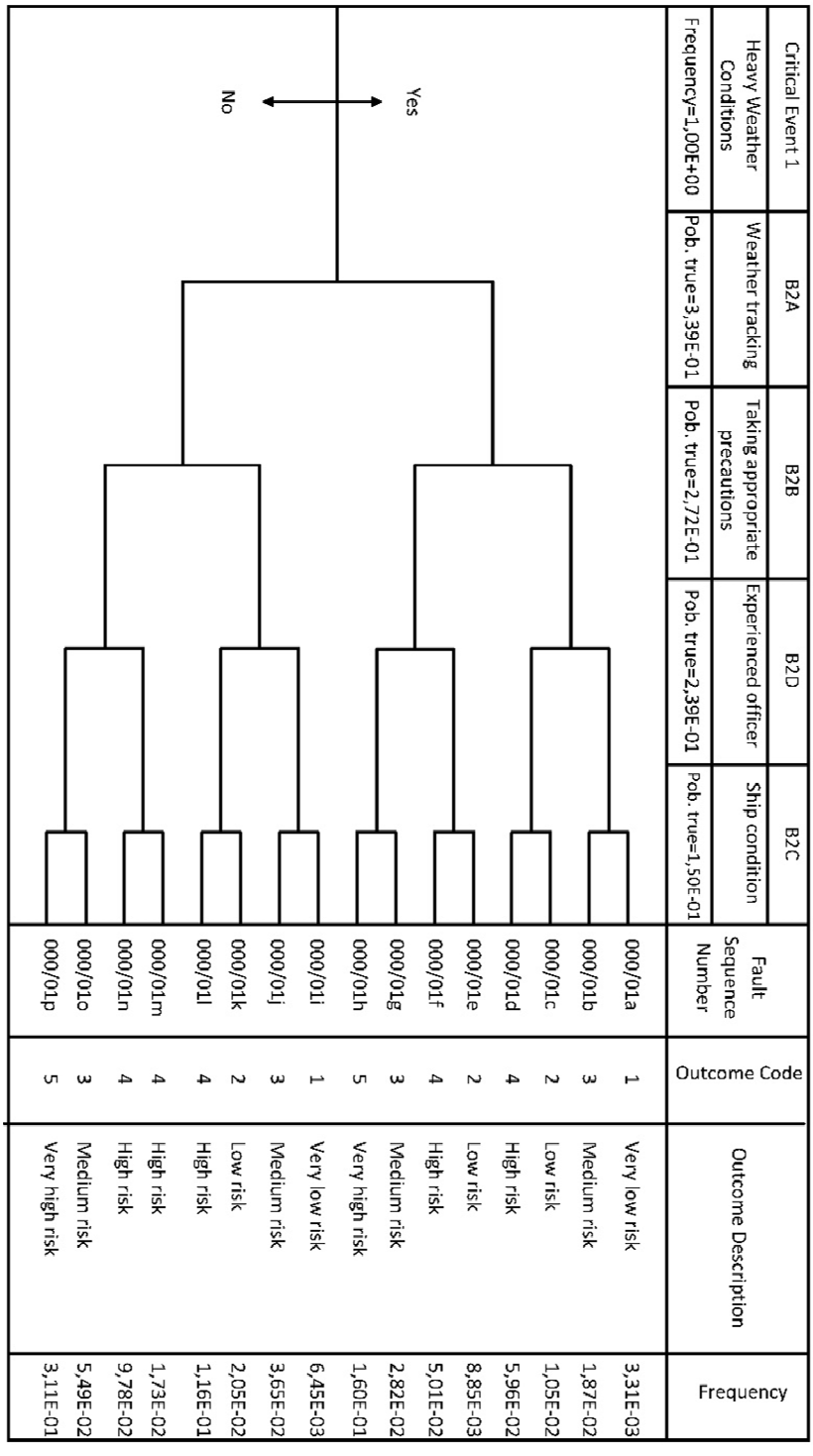


Figure 15 Event tree for UO5 insufficient lookout

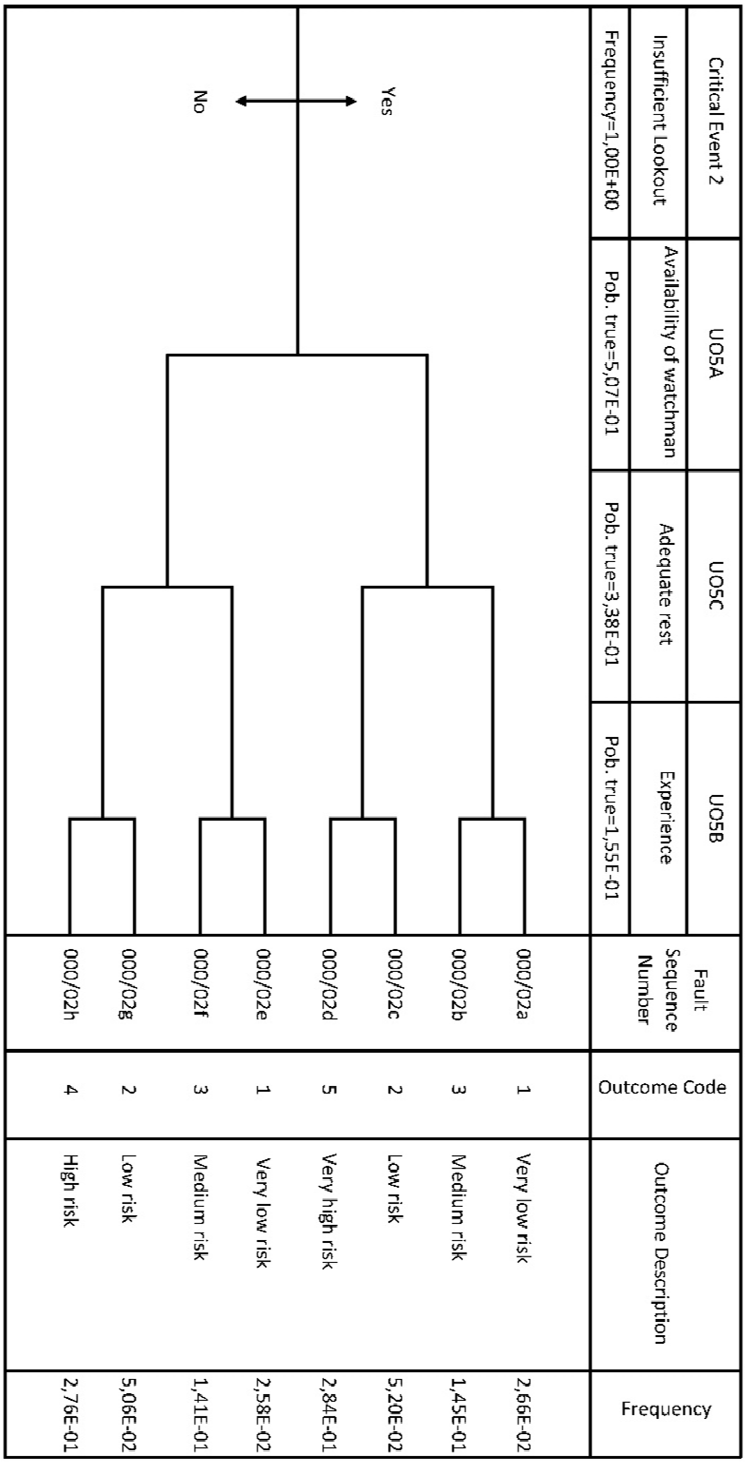
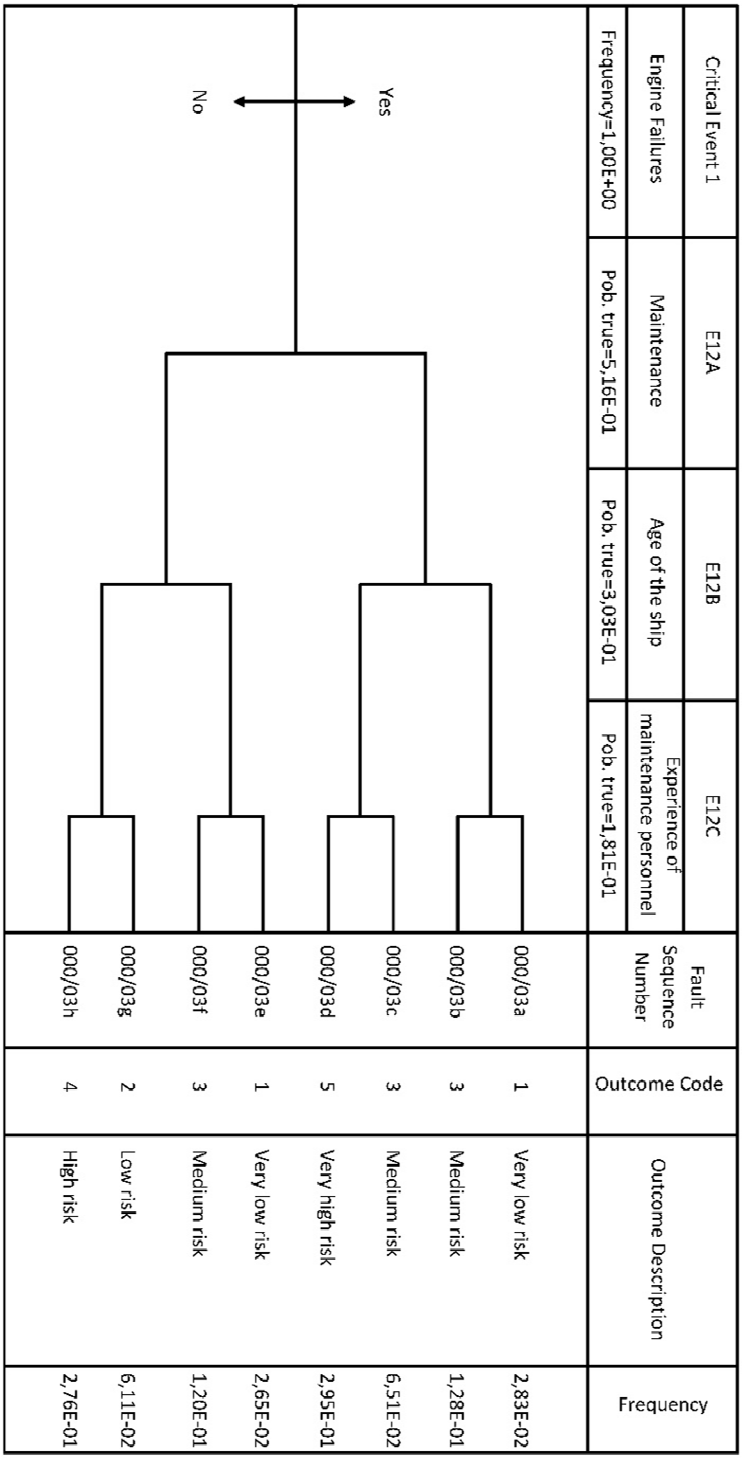


Figure 16 Event tree for E12 engine failure



As a result of the analysis, six important causes were determined by FTA for the ETA analysis. These include three in grounding accidents (Table 6) and three in collision accidents (Table 8). Prevention points were determined by conducting expert consultations in order to prevent the causes determined for the ETA analysis (Table 14). In addition, the probabilities of the prevention points were calculated with the FUCOM method by using the expert opinions. ETA analysis is performed after the calculations, and the risk levels are determined which could occur when prevention points are applied to the causes of the accident (Figures 11–16). Thus, it has been seen that the FTA-FUCOM-ETA hybrid method can suitably be applied for accident analysis.

As the methods used in the study have limitations in themselves, there are also various limitations in using them together. While investigating the causes of accidents with FTA, it is necessary to go down and deep to the smallest detail of each cause. However, the scarcity of available data and the scarcity or lacks of detail in the reports are critical limitations for the study. In ETA, on the other hand, all accident causes must be known in detail and quantitative calculations must be made in order to determine the probability of occurrence of events. Since this is not possible with the available data, the FUCOM method was preferred. Since the FUCOM method also requires expert opinions, experts must have developed themselves and a well experience in their fields. If the appropriate experts are not selected, correct results may not be obtained.

6 Conclusions and recommendations

The risk of accidents has increased with the development of technology in the maritime field, the construction of large ships, and the transport of excessive cargo. Under normal circumstances, the occurrence of accidents can be seen as a normal situation. However, because of accidents in the maritime field, great damage and losses occur. Therefore, knowing the causes of accidents and taking necessary precautions will minimise damage and losses. In this study, navigational accidents between January 2014 and March 2020 are analysed with FTA-FUCOM-ETA method. As a result of the analysis of the data, 110 of the 230 accidents that took place in a period of approximately six years are grounding and 120 are collision accidents. Collision and grounding accidents are statistically analysed according to flag state, ship type, gross tonnage, and severity. In collision accidents, the flag state of Liberia with 27 ships, general cargo type ships with 36 accidents, ships less than 500 GRT and 20,000–50,000 GRT 45 accidents, and serious accident type with 42% according to the severity of the accident are found. When examined in terms of the causes of collision accidents, the main causes that have the most impact and are in the top five are R12 (disobeying the COLREG rules), R13 (insufficient lookout), B5 (storm), B7 (strong winds) and M2 (narrow manoeuvre area). When MCSs that must occur for the identified root causes to occur in collision accidents are examined, the clusters which have the greatest impact are B5 (storm), and R12 (disobeying the COLREG rules) cut sets.

In grounding accidents, the flag state of Malta and Panama with eight ships the most, general cargo type ships with 30 accidents, ships less than 500 GRT with 33 accidents, and serious accident type with 50% according to the severity of the accident are found. When the causes of grounding accidents are examined, the main causes that have the most impact and are in the top 5 are respectively B2 (heavy weather conditions), UO5 (insufficient lookout), E12 (engine failure), B7 (strong winds), E13 (loss of power).

When the MCSs that must occur for the identified root causes to occur in grounding accidents are examined, the clusters that have the greatest impact are the B2 (heavy weather conditions) and UO5 (insufficient lookout) MCSs.

To reduce the accidents caused by navigation, first, it is necessary to have competent and equipped training centres. In addition, necessary support and arrangements should be made for regular inspections of training centres and for trainers to keep up with technological developments/innovations. For instance, to maintain the familiarity of the trainers with the ship, it is important to ensure that they are assigned to the ship at regular intervals in terms of keeping up with the innovations. It is seen that the accidents are caused by the lack of communication and not using a common language. Therefore, necessary measures should be taken to improve English that is the common language of seafarers. In addition, maritime English should be emphasised in educational institutions. Due to increased maritime activities, inspections of freight carriers, flag state inspections, and port state controls, the workload of watch officers is increasing. This situation causes fatigue and erroneous decisions taken by the watch officers. To reduce this situation, relevant companies and organisations should take measures such as employing extra officers. The fact that there are not enough watchmen on the bridge due to the workload and other reasons on the ships and the watch officer's inadequate lookout are among the important factors causing the accident. In order to reduce this situation, it is necessary to increase the personnel working on the ship. Bad weather conditions also play an important role in ship accidents. Ships must necessarily inevitably navigate in bad weather conditions. In this case, to minimise the effect of adverse weather conditions, weather reports should be checked regularly, information should be given about the weather events prevailing in the region at the time, the most appropriate route should be determined and, to avoid the effects, appropriate manoeuvres should be made.

The following results are obtained with ETA for a total of six causes, three for collision accidents and three for grounding accidents.

1 Results for collision accidents:
   - When awareness, education and practice are applied together, the probability of accidents caused by R12 disobeying the COLREG rules are very low. However, if awareness and education are not applied together and practice is not applied, the probability of accidents arising from the R12 disobeying the COLREG rules rises to an upper level (low).
   - When availability of watchman, experience and adequate rest are applied together, the probability of accidents caused by UO5 insufficient lookout becomes very low.
   - When experienced officer, weather tracking, ship condition, and taking appropriate precautions are applied together, the probability of accidents caused by B5 storm is very low.

2 Results for grounding accidents:
   - When weather tracking, taking appropriate precautions, experienced officer and ship condition are applied together, the probability of accidents caused by B2 heavy weather conditions becomes very low.

- When availability of watchman, adequate rest, and experience are applied together, the probability of accidents caused by UO5 insufficient lookout is very low.
- When maintenance, age of the ship and experience of maintenance personnel are applied together, the probability of accidents caused by E12 engine failure becomes very low.

When the ETA results are evaluated, it is seen that the precautionary points determined are appropriate to prevent the causes of the accident.

This study is a resource for knowing the causes of navigational accidents and taking necessary precautions. In addition, since additional measures must be taken to maintain maritime activities in a safe and secure manner, the situations mentioned in this study are important for other studies.

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