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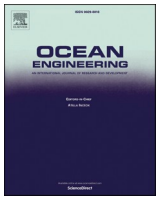



Fuzzy fault tree analysis for loss of ship steering ability

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ABSTRACT

Marine accidents have devastating effects on human life, the environment, and the economy. This study investigated the root causes of accidents resulting from the loss of a ship steering ability using Fuzzy Fault Tree Analysis (FFTA). Failure of the steering gear's hydraulic power, failure of the rudder, and failure of the steering gear's control are the three most common causes of loss of ship steering ability. Due to the difficulty in obtaining exact probabilities, the linguistic judgments of experts were used to determine the probabilities of each event's occurrence. The results showed that "steering gear hydraulic power failure" has the highest occurrence probability, followed by "rudder failure" and "steering gear control failure" in descending order. The occurrence probability of the top event, loss of steering ability, was calculated as 4.86E-02. An examination of the minimum cut set (MCS) identified "oil leaking through sealings to surrounding" as the most dangerous event. The MCS with the lowest occurrence probability was a combination of a main power supply failure and an emergency power supply failure. The findings of this study have made substantial theoretical and applied contributions to maritime safety, environmental protection, and the global economy.

1. Introduction

A significant part of global trade is conducted by sea. Vessels use various routes in maritime transport. Straits and channels are the most hazardous in terms of ship accidents among these routes. Examining past accident statistics revealed that a significant proportion of accidents occurred in straits and channels. This accident can cause structural damage to the ship and endanger the lives of the crew. In addition, it causes serious damage to the global economy by disrupting the supply chain. Although international maritime authorities make great efforts to ensure safe maritime transport, a significant number of maritime accidents occur yearly (Uğurlu et al., 2015).

The accident of the container ship Ever Given in the Suez Canal in 2021 was one of the most recent severe accidents. More than 370 ships were affected by the incident, which caused delays in their voyages. The estimated daily damage to the global economy was approximately $9 billion. Therefore, the total cost of the six-day-long rescue operation was estimated to be 54 billion dollars (Lee and Wong, 2021). The impact of this incident on the global economy was debated by experts and reported by the international media for weeks.

Maritime accidents appear as an essential research topic by researchers as they cause both loss of life and serious damage to the global economy. In the literature, various risk analysis methods are used to reduce or prevent accidents. Some of the traditional methods are Hazard and Operability Study (HAZOP), Failure Modes, and Effect Analysis (FMEA). Today, Fault Tree Analysis (FTA) is widely used to evaluate the safety and reliability of complex systems due to its effectiveness. FTA has been demonstrated as an effective risk analysis technique (Lavasani et al., 2015; Mentes and Helvacioglu, 2011).

The FTA method has a hierarchical structure and includes events and logic gates. An undesired event or accident is considered a top event. The sub-components that cause TE are basic events. To determine the failure probability of TE in traditional FTA, the occurrence probability of all basic events must be known with certainty. In practice, it is extremely difficult to obtain the precise failure probability values for basic events. The traditional FTA approach considers system failure probabilities as precise values. However, data scarcity is a major issue when it comes to calculating component failure rates in the maritime industry. Traditional FTA was processed with fuzzy theory and called the fuzzy FTA (FFTA) method to overcome this problem. This approach incorporates fuzzy logic to deal with uncertainty in the failure probability estimates, thereby improving the accuracy of the analysis.

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There are numerous FFTA applications in a variety of disciplines in the literature. Hu et al. (2019) carried out an application for the unconventional gas industry. In the study, hydraulic fracturing flowback water storage failure was investigated using FFTA. Cheng et al. (2009) studied the emergency shutdown system in the liquefied natural gas receiving terminal by using FFTA. The study by Perveen et al. (2019) can be given as an example of applications in the field of renewable energy. The reliability assessment of solar photovoltaic systems was conducted in the study. Akhtar and Kirmani (2020) performed a different application in the field of renewable energy. They used FFTA for the reliability assessment of the wind power system. Mottahedi and Ataei (2019) used FFTA in the mining area. In the study, the possibility of a coal burst was investigated. Similarly, gas and dust explosion in coal mines was investigated by Shi et al. (2018). Wang et al. (2013) researched crude oil tank fires and explosions. They used FFTA to calculate the occurrence probability of an accident. In another study, Halloul et al. (2019) examined an oil storage tank fire with FFTA.

FFTA is often preferred for risk studies in the maritime field. Mentes and Helvacioglu (2011) carried out an analysis of tanker-buoy spread mooring systems using the FFTA method. In the study, the probability values of the basic events were obtained using the experts' opinions. In addition, simulations of alternative mooring systems were conducted. Kuzu et al. (2019) investigated the risks of ship mooring operations with FFTA. Fault tree construction was based on a real event M/T Zarga's maneuver at the LNG terminal. Twenty-one basic events were determined and a hierarchical structure was created by connecting with logical gates. Şenol et al. (2015) determined the root causes of the cargo contamination and calculated its probability by using FFTA. The aim of the study is to propose a strategy for risk management. Uğurlu et al. (2015) investigated collision and grounding accidents, which are the most common types of accidents seen in oil tankers, by using the FTA method. The study's findings indicated that human error was the primary factor influencing collision and grounding accidents. Şenol and Şahin (2016) analyzed grounding and collision accidents in a dynamic environment with the FFTA method. In the study, conventional BEs were used for non-changing situations. However, the sensor BE and manual BE were proposed for various dynamically changing situations. Akyuz et al. (2020) created a fault tree for risk analysis on cargo liquefaction onboard ships. As a risk analysis technique, the bow-tie method, which combines FTA and ETA, was employed. Ünver et al. (2019) used the FFTA method for crankcase explosion in a two-stroke marine diesel engine. A pentagon containing the effective parameters for the crankcase explosion was presented. After the crankcase explosion mechanism was introduced, the fault tree was constructed and analyses were conducted. Li et al. (2022) conducted a fire risk assessment study on ship power systems. They utilized expert evaluations on the construction and analysis phases of basic events with FFTA. The results showed that the fire frequency is 5.23E-6 per hour and the fuel system has the highest fire risk in a ship engine room and the role of human factors in maritime transportation accidents was analyzed in the study of Zaib et al. (2022) by using FFTA. The potential causes of grounding accidents are evaluated to obtain the quantified contribution of human errors on the case accident. The study indicated that the main contributor to the accident was the inaccurate information provided about the seaport conditions with a probability value of 5.27E-02. Tunçel et al. (2023) used the FFTA method to assess the risk of fire and explosion accidents in bulk carriers. The study aimed to reduce the risk of fire and explosion accidents on bulk carriers, which was obtained as 9.27E-02, by introducing the potential faults to improve operational safety.

The studies on risk analysis were conducted in a variety of maritime fields. The FFTA is obtained as a widely and successfully adopted method in these studies. There are found very limited studies in the field of risk assessment of ship steering systems. Göksu et al. (2023) assessed the risk of ship steering gear systems by investigating the steering gear caused accident reports in their study based on the fuzzy-Bayesian networks method. The results of the study indicate that the probability of a steering gear accident is 13.7% under the best-case scenario. Component-related electrical failures and hydraulic oil-sourced faults are found to be the most significant contributors to steering gear system-caused accidents. The study does not involve critical risks that may cause loss of steering ability, e.g., rudder failures, human errors, blackouts, and malfunctions in the propulsion system. In addition, there are no specific and applicable recommendations. In this regard, the main motivation of this study can be expressed as to establish a comprehensive fault tree for evaluating the risks that may lead to loss of steering ability on marine vessels, and cause serious loss of life and property. The riskiest events are determined using FFTA and some suggestions are presented to reduce the probability of these risks. Understanding the root causes of these accidents can contribute to the improvement of safety regulations and the development of reliable and efficient steering mechanisms. It can also contribute to the creation of better training programs for sailors and crew members. Ultimately, investigating these accidents can lead to enhanced safety measures and practices, creating a safer environment for everyone on board ships.

In this study, the events that create a risk of losing the steering ability on marine vessels were assessed using the frequently preferred FFTA method. In this context, after brainstorming with experienced field experts, a fault tree was created. The linguistic expressions of the experts were collected to provide the probability of each basic event and converted to fuzzy numbers. Then, the stages of the FFTA method were implemented. Later, the top event and Minimal Cut Sets (MCSs) probabilities were calculated. The MCSs were subsequently ranked by risk, and the results were interpreted.

FFTA was utilized in this study as a powerful safety analysis technique widely accepted in many disciplines, particularly the maritime sector. When constructing the fault tree for the loss of steering system ability event, not only the mechanical and electrical components of the system that cause the loss of ship steering ability but also human errors that may affect the emergency steering gear procedure were taken into account. It is known that human errors caused by the lack of information related to the emergency steering gear procedure have also led to the loss of ship steering ability. This study includes critical risks such as rudder failures, ship power system failures, and propulsion system failures. Additionally, it provides practical and effective recommendations to prevent accidents and improve the overall safety of the ship's operations. All of these are considered as strong contributions to the originality of the study.

The remainder of this paper is organized as follows. Section 2 gives the theoretical background of the FFTA method. Section 3 includes the problem statement and the construction of the fault tree. Implementation is addressed in Section 4 of the paper. Section 5 gives the results and discussion. Section 6 concludes the paper with a discussion of the study's key contributions and recommendations.

2. Fuzzy fault tree analysis method

FTA is one of the most well-known methods for conducting safety analysis. The key advantages of FTA are: (i) it provides significant ease in identifying the risks of complex systems, (ii) it facilitates the identification of risks in complex systems, (iii) it makes the consequences of errors visible, (iv) it makes probability estimates and (v) analysis results are easy to understand (Smith, 2001). FTA essentially consists of events and logic gates that connect events. As depicted in Fig. 1, various symbols are used to construct trees.

The event has more basic events and it is displayed as a rectangle. Basic events are basic failures in the system and are shown as circles. If there is no existing knowledge on an event, it is referred to as an "undeveloped event". The AND Gate is used if the occurrence of an output depends on the occurrence of all input events together. If an output occurs with any of the inputs, an OR Gate is used. The transfer symbol is used to detail the tree at another place (Senol et al., 2015).

In conventional FTA, the probability of failure of basic events (BEs)

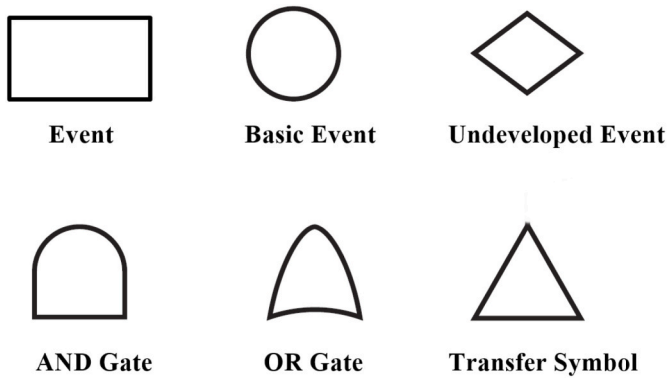

Fig. 1. Symbols used in FTA.

must be known. These are considered as crisp values. However, obtaining this information is an extremely challenging procedure in real life. The most practical approach to solving this problem is to use fuzzy logic, which is referred to in the literature as FFTA (Lavasani et al., 2015). FFTA is a complex method consisting of many steps and these are shown below.

2.1. Aggregating stage

The Similarity Aggregation Method introduced by Hsu and Chen (1996) was used to aggregate the judgments of the experts. First, linguistic terms are defined and explained to experts. Next, each expert expresses his or her own opinion in linguistic terms for the relevant event. The linguistic terms of M experts $E_k(k = 1, 2, \ldots, M)$ for all events are recorded. The linguistic terms are converted into fuzzy numbers. Thus, the preliminary preparations for the aggregating stage are completed. The steps required to complete the aggregating stage are explained below.

- **Calculate the degree of similarity:**

The degree of similarity of the expert pairs denoted by "R" is expressed by "S". Where $S_{uv}(\widetilde{\mathrm{R}}_u, \widetilde{\mathrm{R}}_v) \in [0,1]$ Also, $\widetilde{\mathrm{R}}_u = (\mathrm{r}_{u1}, \mathrm{r}_{u2}, \mathrm{r}_{u3}, \mathrm{r}_{u4})$ and $\widetilde{\mathrm{R}}_v = (\mathrm{r}_{v1}, \mathrm{r}_{v2}, \mathrm{r}_{v3}, \mathrm{r}_{v4})$ are two standard trapezoidal fuzzy numbers. The similarity function is used to determine the degree of similarity between these two experts' opinions.

$$S(\widetilde{\mathrm{R}}_u, \widetilde{\mathrm{R}}_v) = 1 - \frac{1}{4}\sum_{i=1}^{4} |r_{ui} - r_{vi}| \tag{1}$$

A greater value of $S(\widetilde{\mathrm{R}}_u, \widetilde{\mathrm{R}}_v)$ means greater similarity between the two opinions.

- **Calculate the average agreement degree of the experts:**

The average agreement degree of the experts ($AA(E_u)$) is calculated by the following equation.

$$AA(E_u) = \frac{1}{M-1}\sum_{\substack{u \neq v \\ v=1}}^{N} S(\widetilde{\mathrm{R}}_u, \widetilde{\mathrm{R}}_v) \tag{2}$$

- **Calculate the relative agreement degree of the experts:**

The relative agreement degree of the experts ($RA(E_u)$) is determined as follows:

$$RA(E_u) = \frac{AA(E_u)}{\sum_{u=1}^{N} AA(\mathrm{E}_u)} \tag{3}$$

- **Calculate the consensus coefficient degree of the experts**

The consensus coefficient degree of the experts ($CC(E_u)$) is determined as follows:

$$CC(E_u) = \beta.w(E_u) + (1-\beta)\cdot RA(E_u) \tag{4}$$

- **Aggregate results of the judgments of experts**

Aggregate results of the judgments of experts ($\widetilde{R}_{AG}$) are obtained as follows:

$$\widetilde{R}_{AG} = CC(\mathrm{E}_1) \times \widetilde{R}_1 + CC(E_2) \times \widetilde{R}_2 + \ldots + CC(\mathrm{E}_M) \times \widetilde{R}_M \tag{5}$$

2.2. Defuzzification stage

The defuzzification process converts fuzzy numbers into crisp numbers for analysis and decision-making in the fuzzy environment. The Center of Area (COA) introduced by Sugeno (1999) was used for the defuzzification stage of this study.

$$X^* = \frac{\int \mu_i(x) x dx}{\mu_i(x)} \tag{6}$$

where X^* is defuzzified output, $\mu_i(x)$ is aggregated membership function and x is output variable. The defuzzification for trapezoidal fuzzy numbers can be expressed as:

$$X^* = \frac{\int_{r_1}^{r_2} \frac{x-r}{r_2-r_1} x dx + \int_{r_2}^{r_3} x dx + \int_{r_3}^{r_4} \frac{r_4-x}{r_4-r_3} x dx}{\int_{r_1}^{r_2} \frac{x-r_1}{r_2-r_1} dx + \int_{r_2}^{r_3} x dx + \int_{r_3}^{r_4} \frac{r_4-x}{r_4-r_3} dx} = \frac{1(\mathrm{r}_4+r_3)^2 - r_4 r_3 - (\mathrm{r}_1+r_2)^2 + r_1 r_2}{r_4+r_3-r_2-r_1} \tag{7}$$

Thus, trapezoidal fuzzy numbers are converted to crisp values. These are the possibility values for the relevant events.

2.3. Converting possibility values to failure probability values

The crisp failure possibility (CFP) of each basic event is converted to failure probability (FP).

$$FP = \begin{cases} \frac{1}{10^K}, & CFP \neq 0 \\ 0, & CFP = 0 \end{cases} \tag{8}$$

where K is the coefficient and is obtained as follows:

$$K = \left[\left(\frac{1-CFP}{CFP}\right)\right]^{\frac{1}{3}} \times 2.301 \tag{9}$$

2.4. Calculating of MCS and overall probability of the top event

A fault tree has more than one basic event and these are interconnected by various gates. Minimum cut sets (MCS) are used to obtain the probability of a top event (TE). MCS is a combination of BEs and the occurrence of all these events means the emergence of TE. Each fault tree has its unique number of MCSs. The probability of TE occurrence is calculated as follows:

$$P(TE)=P(MCS_1\cup MCS_2\cup\ldots\cup MCS_N)=P(MCS_1)+P(MCS_2)+\ldots P(MCS_N)$$
$$-\left(P(MCS_1\cap MCS_2)+\left(P(MCS_1\cap MCS_3)+\ldots\left(P\left(MCS_i\cap MCS_j\right)\ldots\right)\ldots\right.\right.$$
$$+(-1)^{N-1}P(MCS_1\cap MCS_2\cap\ldots\cap MCS_N) \quad (10)$$

where, $P(MCS_i)$ the occurrence probability of MCS_i and N is the number of MCS.

2.5. Ranking of MCS and sensitivity analysis

The contribution of MCSs to the top event is a crucial topic. The top event probability is a useful metric to understand the overall condition of a system. However, to gain deeper insights into the system's failure modes, a sensitivity analysis is required to assess the individual contribution of each basic event that leads to a top event. Sensitivity analysis also provides an estimation of the unavailability and failure frequencies of each basic event. In addition, this analysis facilitates the identification of crucial system decisions, such as the weakest component, the exploration of enhanced design alternatives, and the evaluation of the effect of a chosen solution on system safety (Ferdous et al., 2009).

The term "cutsets importance" is frequently used in the context of sensitivity analysis, according to a review of the relevant literature (Arici et al., 2020; Ferdous et al., 2009, Unver et al., 2019).

Fussell-Vesely Importance Measure (F-VIM) is used to determine the cutset's contribution to the top event. In this study, F-VIM was used for conducting sensitivity analysis and is calculated as follows:

$$I_i^{FV}(t)=\frac{Q_i(t)}{Q_S(t)} \quad (11)$$

where $I_i^{FV}(t)$ is the importance of MCS, $Q_i(t)$ is the contribution of each MCS to failure probability and $Q_S(t)$ is the probability of failure of TE.

3. Problem statement and construction of fault tree

The steering ability of ships is provided by the integration of a steering gear system with a rudder. Modern ships are equipped with electro-hydraulic type steering gear systems that can control the rudder angle in either direction by a signal given from the bridge. The main steering gear units shall be capable of putting the ship's rudder over from 35° on either side to 30° on the other side in not more than 28 s while the ship is running at maximum ahead. An auxiliary steering gear unit shall be fitted as a backup for emergency situations. The main steering gear shall comprise two or more identical power units instead of an auxiliary steering gear in every tanker/gas carrier of above 10,000 gross tonnages and every other ship of 70,000 gross tonnages (IMO and IMO, 2011). When the required rudder angle command is given from the helm in the bridge control room, a signal is delivered to the telemotor system of steering gear to control the servo controllers. The servo controller adjusts the valve blocks to direct the hydraulic oil to the hydraulic rudder actuator. The solenoid valves in the servo controller unit shall also be operated manually from the steering gear room in accordance with the emergency steering gear procedures of the vessel. The tiller connected to the rudder actuator receives the mechanical force and starts to turn the rudder in the designated direction. The return oil drains down to the hydraulic reservoir of the power unit. The hydraulic oil is continuously supplied to servo controller units in a closed loop circuit to keep a constant hydraulic pressure in the system as long as the steering gear system is operational. Coolers are fitted to each hydraulic power unit to ensure the oil temperature remains within specified limits. Rotary vane and ram types of hydraulic rudder actuators are utilized in marine vessels (McGeorge, 1998). A simple schematic of a ram type steering gear system is illustrated in Fig. 2.

The loss of steering ability of a ship may occur from failures related to the rudder, steering gear control units, or hydraulic power supply to the steering gear system. Since hydraulic oil is used for power transmission, changes in hydraulic oil properties would have a significant impact on the working conditions of hydraulic pumps, motors, and rudder actuators (Han et al., 2020). In case of a blackout (when the diesel generators of the vessel are inoperable), the emergency generator shall supply power to the one hydraulic power unit, designated as an emergency unit, through the emergency switchboard. If the emergency generator cannot be operated in blackouts, the power supply to the steering gear system will obviously fail. Human errors related to maintenance activities or lack of knowledge may cause failures in power and control systems of the steering gear system (Bureau, 2016). In addition, failures in electrical equipment, their connections and sensors would disable the telemotor system and result in not transmitting the signals given from the bridge control room (Mohović et al., 2013; Zhang and Li, 2014). Rudders regulate the flow of water in any given direction. Therefore, failures in propellers or flow arrangements would affect the rudder performance as the water flow would be stopped or misdirected. The rudder jamming can also be given as a type of failure that would cause grounding or collision of marine vessels (Gucma et al., 2021). The

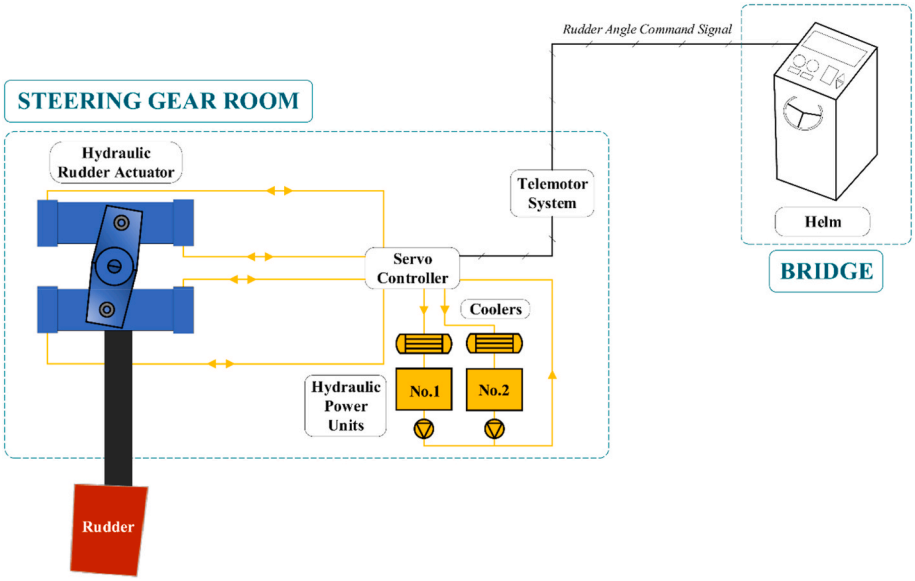

Fig. 2. Schematic of a ram type electro-hydraulic steering gear system in ships.

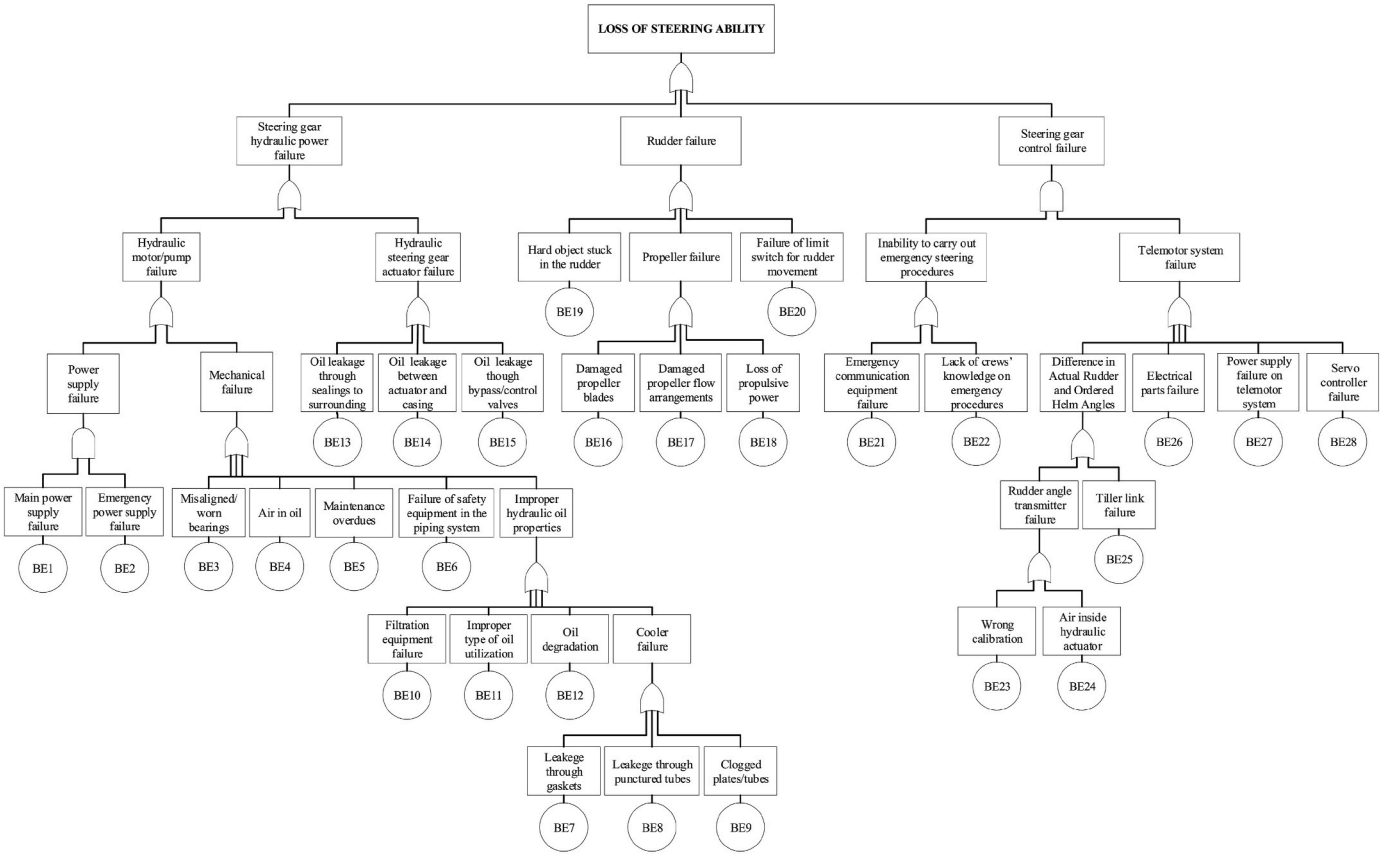

Fig. 3. Fault tree diagram.

structure of the fault tree for the loss of steering ability was given in Fig. 3.

4. Implementation

4.1. Collecting of linguistic judgments of experts

Initially, the experts were determined at this stage. As is well known, experts have varied personal experiences, so their perspectives on a topic differ. Selecting a diverse group of experts ensures that all perspectives are taken into account. Therefore, selecting a diverse group of experts is preferable to selecting a homogenous group. Each expert's evaluation was assessed using a relative weighting score. The weighting scores of the experts were assigned according to their professional position, work experience and education level. Similar evaluations have been used in many studies (Kum and Sahin, 2015; Kuzu et al., 2019; Lavasani et al., 2015; Senol et al., 2015; Senol and Sahin, 2016, Unver et al., 2019; Yazdi et al., 2017). Expert classification and weighting scores are given in Table 1.

Table 1
Expert classification and scores.

Parameter	Classification	Score
Professional Position	Chief engineer	3
	2nd engineer	2
	3th or 4th engineer	1
Work Experience	>10 year	3
	5–10 year	2
	<5 year	1
Educational Level	Ph.D.	3
	Master	2
	Bachelor	1

Table 2
Expert profile and their weighting score.

Experts	Professional position	Work experience (years)	Education level	Total weight	Weighting score
1	2nd engineer	11	Ph.D.	8	0.22
2	Chief engineer	11	BSc.	7	0.19
3	3th or 4th engineer	13	PhD.	7	0.19
4	2nd engineer	10	PhD.	8	0.22
5	3th or 4th engineer	7	PhD.	6	0.17

A heterogeneous group of five experts was selected for this study. The profiles and relative weighting scores of the experts in this group are displayed in Table 2.

After the experts were determined, the probability evaluation process was started for the basic events. This assessment was carried out using linguistic terms. The determination of linguistic terms is a major issue, as experts evaluate the basic events using linguistic terms. Considering the memory capacity of the human brain, a linguistic term number between 5 and 9 provides a more realistic assessment (Lavasani et al., 2015; Nicolis and Tsuda, 1985). In this study, the number of linguistic terms was determined as 7. The linguistic terms were very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H) and very high (VH). As a result, the evaluation performed by the experts for each basic event was obtained as in Table 3.

4.2. Converting of linguistic judgments to fuzzy numbers

At this stage, the linguistic terms were converted to fuzzy numbers.

Table 3
Expert judgments for each basic event.

	E1	E2	E3	E4	E5
BE1	L	MH	L	VH	ML
BE2	VL	L	VL	ML	L
BE3	L	M	VL	MH	M
BE4	ML	ML	VL	L	ML
BE5	M	H	VL	M	H
BE6	L	ML	VL	ML	M
BE7	L	ML	MH	M	H
BE8	L	L	L	ML	MH
BE9	ML	M	ML	MH	MH
BE10	L	H	ML	ML	M
BE11	VL	MH	L	VL	ML
BE12	VL	MH	M	MH	M
BE13	ML	MH	ML	VH	H
BE14	L	H	L	MH	M
BE15	VL	ML	VL	M	M
BE16	VL	L	ML	VL	L
BE17	VL	L	VL	VL	ML
BE18	H	L	L	MH	M
BE19	L	L	L	VL	L
BE20	VL	L	ML	MH	ML
BE21	L	M	ML	VL	M
BE22	MH	MH	M	H	VH
BE23	M	H	VL	M	VH
BE24	L	ML	L	ML	M
BE25	L	MH	VL	VL	M
BE26	L	MH	L	VH	MH
BE27	L	M	ML	H	M
BE28	L	MH	L	ML	M

Table 4
Linguistic terms and fuzzy numbers.

Linguistic term	Fuzzy numbers
Very low (VL)	(0.0, 0.0, 0.1, 0.2)
Low (L)	(0.1, 0.2, 0.2, 0.3)
Medium low (ML)	(0.2, 0.3, 0.4, 0.5)
Medium (M)	(0.4, 0.5, 0.5, 0.6)
Medium high (MH)	(0.5, 0.6, 0.7, 0.8)
High (H)	(0.7, 0.8, 0.8, 0.9)
Very High (VH)	(0.8, 0.9, 1.0, 1.0)

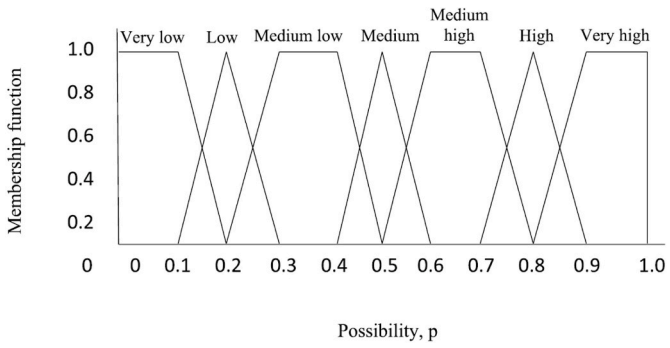

Fig. 4. Trapezoidal fuzzy numbers and membership functions.

Similar to many other studies, trapezoidal fuzzy numbers were used in this study. Linguistic terms and fuzzy numbers are given in Table 4 and Fig. 4 shows fuzzy rating and membership functions.

Thus, the prerequisite procedures for applying the FFTA approach have been completed. In the next section, the fundamental FFTA implementation procedures are briefly described.

4.3. Implementation of the FFTA

At this point, each expert evaluated the relevant basic events. First, the evaluation of each expert was aggregated. Following the procedures outlined in Section 2.1, the aggregate results of the experts' evaluations were obtained. Later, the defuzzification process was performed and the possibility values were converted to failure probability values. Finally, the probabilities of the top event and MCSs were calculated. In the following part, the results and comments of all the steps performed are systematically presented.

5. Results and discussion

Firstly, the degree of similarity was calculated and presented in Table 5. In the table, *S(E1&E2)* represents the similarity of the opinion of expert 1 and expert 2 for each BE. For example, *S(E1&E2)* for *BE1* is equal to 0.55, so the similarity is 55%. In addition, the value of *S (E1&E2)* for *BE4* was obtained as 1. This result shows that Expert 1 and Expert 2 are entirely in agreement with each other on the *BE4*.

The comparison of the relevant expert opinion for each BE with all the expert opinions is obtained with the calculation of the average agreement of expert. The results of average agreement calculations for each BE are presented in Table 6. For example, the least consensus for *BE1* was calculated as 0.425 with Expert 4. Relative agreement values for each BE are given in Table 7. The procedure performed here is actually a normalization between the values of 0 and 1.

In this study, all experts were accepted as having the same expertise, and the beta coefficient shown in Equation (4) was taken as 0.5. Then the consensus of coefficients (CC) for each BE is calculated and the results are shown in Table 8.

As the last step of the aggregation process, trapezoidal fuzzy numbers are assigned for each BE. This step is the summation process of multiplying the consensus coefficients and each value of corresponding fuzzy numbers. The aggregation of BEs is shown in Table 9.

The defuzzification process was performed using the center of area method for final fuzzy numbers and the obtained crisp values are shown in Table 10. It is important to point out that crisp values are the possibility values obtained from the fuzzy process. Therefore, it is an essential issue to convert possibility values into probability values with a scientific approach. The probability value of the BE13 is the greatest, while the probability value associated with the BE17 is the lowest.

After obtaining the probability values for all BEs, the top event probability was calculated considering the structure of the constructed fault tree. Also, all MCSs for the top event were determined and their probabilities were obtained. As a result, the top event probability was calculated as 4.86E-02. The occurrence probabilities of each MCS and their FV-I values are given in Table 11.

MCS is the smallest combination of basic events that, when they occur together, lead to the top event in the fault tree. In other words, it is the smallest set of events that, if any one of them fails, will cause the entire system to fail. FV-I shows the contribution of MCSs in the occurrence of the top event. The results showed that all the top five MCSs were related to the steering gear hydraulic power failure. The riskiest event was determined as "oil leakage through sealings to surrounding" called BE13. BE13 causes the hydraulic steering gear actuator failure, causing the main event of the steering gear hydraulic power failure. Thus, loss of steering ability can occur. When the top 10 MCSs are examined, only 2 MCSs are related to rudder failure, while the rest are related to steering gear hydraulic power failure. When all the results are evaluated together, the riskiest ones in terms of main events are related to steering gear hydraulic power failure, followed by rudder failure and steering gear control failure, respectively. The power supply failure was found to have the lowest occurrence probability among MCSs. Main power supply failure and emergency power supply failure are the two basic events that lead to power supply failure, and they are connected by an AND gate. In other words, if these two basic event occurrences take place simultaneously, a power supply failure happens on the board. Current experience indicates that the probability of these two basic events occurring simultaneously is extremely low. As a

Table 5
Similarity function and corresponding values for each BE.

	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8	BE9	BE10	BE11	BE12	BE13	BE14
S(E1&E2)	0.55	0.875	0.7	1	0.7	0.85	0.85	1	0.85	0.4	0.425	0.425	0.7	0.4
S(E1&E3)	1	1	0.875	0.725	0.575	0.875	0.55	1	1	0.85	0.875	0.575	1	1
S(E1&E4)	0.275	0.725	0.55	0.85	1	0.85	0.7	0.85	0.7	0.85	1	0.425	0.425	0.55
S(E1&E5)	0.85	0.875	0.7	1	0.7	0.7	0.4	0.55	0.7	0.7	0.725	0.575	0.55	0.7
S(E2&E3)	0.55	0.875	0.575	0.725	0.275	0.725	0.7	1	0.85	0.55	0.55	0.85	0.7	0.4
S(E2&E4)	0.725	0.85	0.85	0.85	0.7	1	0.85	0.85	0.85	0.55	0.425	1	0.725	0.85
S(E2&E5)	0.7	1	1	1	1	0.85	0.55	0.55	0.85	0.7	0.7	0.85	0.85	0.7
S(E3&E4)	0.275	0.725	0.425	0.875	0.575	0.725	0.85	0.85	0.7	1	0.875	0.85	0.425	0.55
S(E3&E5)	0.85	0.875	0.575	0.725	0.275	0.575	0.85	0.55	0.7	0.85	0.85	1	0.55	0.7
S(E4&E5)	0.425	0.85	0.85	0.85	0.7	0.85	0.7	0.7	1	0.85	0.725	0.85	0.875	0.85
	BE15	**BE16**	**BE17**	**BE18**	**BE19**	**BE20**	**BE21**	**BE22**	**BE23**	**BE24**	**BE25**	**BE26**	**BE27**	**BE28**
S(E1&E2)	0.725	0.875	0.875	0.4	1	0.875	0.7	1	0.7	0.85	0.55	0.55	0.7	0.55
S(E1&E3)	1	0.725	1	0.4	1	0.725	0.85	0.85	0.575	1	0.875	1	0.85	1
S(E1&E4)	0.575	1	1	0.85	0.875	0.425	0.875	0.85	1	0.85	0.875	0.275	0.4	0.85
S(E1&E5)	0.575	0.875	0.725	0.7	1	0.725	0.7	0.725	0.575	0.7	0.7	0.55	0.7	0.7
S(E2&E3)	0.725	0.85	0.875	1	1	0.85	0.85	0.85	0.275	0.85	0.425	0.55	0.85	0.55
S(E2&E4)	0.85	0.875	0.875	0.55	0.875	0.55	0.575	0.85	0.7	1	0.425	0.725	0.7	0.7
S(E2&E5)	0.85	1	0.85	0.7	1	0.85	1	0.725	0.875	0.85	0.85	1	1	0.85
S(E3&E4)	0.575	0.725	1	0.55	0.875	0.7	0.725	0.7	0.575	0.85	1	0.275	0.55	0.85
S(E3&E5)	0.575	0.85	0.725	0.7	1	1	0.85	0.575	0.15	0.7	0.575	0.55	0.85	0.7
S(E4&E5)	1	0.875	0.725	0.85	0.875	0.7	0.575	0.875	0.575	0.85	0.575	0.725	0.7	0.85

Table 6
Average agreement of experts for each BE.

	E1	E2	E3	E4	E5		E1	E2	E3	E4	E5
BE1	0.669	0.631	0.669	0.425	0.706	**BE15**	0.719	0.788	0.719	0.750	0.750
BE2	0.869	0.900	0.869	0.788	0.900	**BE16**	0.869	0.900	0.788	0.869	0.900
BE3	0.706	0.781	0.613	0.669	0.781	**BE17**	0.900	0.869	0.900	0.900	0.756
BE4	0.894	0.894	0.763	0.856	0.894	**BE18**	0.588	0.663	0.663	0.700	0.738
BE5	0.744	0.669	0.425	0.744	0.669	**BE19**	0.969	0.969	0.969	0.875	0.969
BE6	0.819	0.856	0.725	0.856	0.744	**BE20**	0.688	0.781	0.819	0.594	0.819
BE7	0.625	0.738	0.738	0.775	0.625	**BE21**	0.781	0.781	0.819	0.688	0.781
BE8	0.850	0.850	0.850	0.813	0.588	**BE22**	0.856	0.856	0.744	0.819	0.725
BE9	0.813	0.850	0.813	0.813	0.813	**BE23**	0.713	0.638	0.394	0.713	0.544
BE10	0.700	0.550	0.813	0.813	0.775	**BE24**	0.850	0.888	0.850	0.888	0.775
BE11	0.756	0.525	0.788	0.756	0.750	**BE25**	0.750	0.563	0.719	0.719	0.675
BE12	0.500	0.781	0.819	0.781	0.819	**BE26**	0.594	0.706	0.594	0.500	0.706
BE13	0.669	0.744	0.669	0.613	0.706	**BE27**	0.663	0.813	0.775	0.588	0.813
BE14	0.663	0.588	0.663	0.700	0.738	**BE28**	0.775	0.663	0.775	0.813	0.775

Table 7
Relative agreement of experts for each BE.

	E1	E2	E3	E4	E5		E1	E2	E3	E4	E5
BE1	0.216	0.204	0.216	0.137	0.228	**BE15**	0.193	0.211	0.193	0.201	0.201
BE2	0.201	0.208	0.201	0.182	0.208	**BE16**	0.201	0.208	0.182	0.201	0.208
BE3	0.199	0.220	0.173	0.188	0.220	**BE17**	0.208	0.201	0.208	0.208	0.175
BE4	0.208	0.208	0.177	0.199	0.208	**BE18**	0.175	0.198	0.198	0.209	0.220
BE5	0.229	0.206	0.131	0.229	0.206	**BE19**	0.204	0.204	0.204	0.184	0.204
BE6	0.205	0.214	0.181	0.214	0.186	**BE20**	0.186	0.211	0.221	0.160	0.221
BE7	0.179	0.211	0.211	0.221	0.179	**BE21**	0.203	0.203	0.213	0.179	0.203
BE8	0.215	0.215	0.215	0.206	0.149	**BE22**	0.214	0.214	0.186	0.205	0.181
BE9	0.198	0.207	0.198	0.198	0.198	**BE23**	0.238	0.213	0.131	0.238	0.181
BE10	0.192	0.151	0.223	0.223	0.212	**BE24**	0.200	0.209	0.200	0.209	0.182
BE11	0.212	0.147	0.220	0.212	0.210	**BE25**	0.219	0.164	0.210	0.210	0.197
BE12	0.135	0.211	0.221	0.211	0.221	**BE26**	0.192	0.228	0.192	0.161	0.228
BE13	0.197	0.219	0.197	0.180	0.208	**BE27**	0.182	0.223	0.212	0.161	0.223
BE14	0.198	0.175	0.198	0.209	0.220	**BE28**	0.204	0.174	0.204	0.214	0.204

consequence, this finding is not surprising.

The loss of steering ability is a critical failure mode in ships that can have serious consequences, including collisions, groundings, and other types of accidents. Therefore, it is essential to develop effective measures to prevent and mitigate such failures. According to the findings, some concrete and applicable suggestions can be proposed. The possibility of hydraulic power loss could be eliminated by utilizing planned or pro-active maintenance activities on the hydraulic actuator and pump/motor parts on time. Especially, the drydock periods to inspect the condition of steering gear and the use of original parts are important points to be considered to prevent major failures, and thus accidents due to the loss of steering ability. Since the hydraulic system of the steering gear contains high pressure elements, the leakage of hydraulic oil from several parts may also cause injuries to crew members nearby. Onboard and/or laboratory tests of the hydraulic oil are also essential, which might reduce the possibility of oil degradation and thus mechanical

Table 8
Consensus of the coefficient for each BE.

	CC1	CC2	CC3	CC4	CC5		CC1	CC2	CC3	CC4	CC5
BE1	0.218	0.197	0.203	0.179	0.199	**BE15**	0.206	0.201	0.191	0.211	0.186
BE2	0.210	0.199	0.195	0.201	0.189	**BE16**	0.210	0.199	0.186	0.210	0.189
BE3	0.209	0.205	0.181	0.204	0.195	**BE17**	0.214	0.195	0.199	0.214	0.172
BE4	0.214	0.199	0.184	0.210	0.189	**BE18**	0.198	0.194	0.194	0.214	0.195
BE5	0.224	0.198	0.160	0.224	0.188	**BE19**	0.212	0.197	0.197	0.202	0.187
BE6	0.212	0.202	0.186	0.217	0.178	**BE20**	0.203	0.201	0.206	0.190	0.196
BE7	0.199	0.200	0.200	0.221	0.174	**BE21**	0.211	0.196	0.201	0.199	0.186
BE8	0.218	0.203	0.203	0.213	0.159	**BE22**	0.217	0.202	0.188	0.212	0.176
BE9	0.209	0.199	0.194	0.209	0.184	**BE23**	0.229	0.201	0.161	0.229	0.176
BE10	0.206	0.170	0.206	0.221	0.191	**BE24**	0.210	0.199	0.195	0.214	0.176
BE11	0.216	0.168	0.205	0.216	0.190	**BE25**	0.219	0.177	0.200	0.215	0.184
BE12	0.178	0.201	0.206	0.216	0.196	**BE26**	0.206	0.209	0.191	0.191	0.199
BE13	0.208	0.204	0.193	0.200	0.189	**BE27**	0.201	0.206	0.201	0.190	0.196
BE14	0.209	0.183	0.194	0.214	0.195	**BE28**	0.212	0.182	0.197	0.217	0.187

Table 9
Aggregation of each BE.

BE1	**0.323**	**0.423**	**0.480**	**0.562**	BE15	**0.199**	**0.258**	**0.318**	**0.418**
BE2	0.079	0.138	0.199	0.298	**BE16**	0.076	0.133	0.194	0.294
BE3	0.283	0.364	0.403	0.502	**BE17**	0.054	0.091	0.171	0.270
BE4	0.141	0.222	0.301	0.400	**BE18**	0.362	0.462	0.483	0.583
BE5	0.450	0.533	0.549	0.649	**BE19**	0.079	0.159	0.179	0.278
BE6	0.176	0.257	0.318	0.417	**BE20**	0.195	0.275	0.354	0.454
BE7	0.370	0.470	0.510	0.610	**BE21**	0.215	0.294	0.334	0.434
BE8	0.185	0.284	0.321	0.421	**BE22**	0.574	0.673	0.733	0.815
BE9	0.357	0.456	0.536	0.635	**BE23**	0.464	0.548	0.581	0.663
BE10	0.302	0.401	0.444	0.544	**BE24**	0.194	0.293	0.335	0.434
BE11	0.143	0.199	0.278	0.378	**BE25**	0.184	0.242	0.301	0.401
BE12	0.369	0.450	0.510	0.609	**BE26**	0.396	0.496	0.555	0.636
BE13	0.475	0.574	0.655	0.734	**BE27**	0.355	0.454	0.474	0.574
BE14	0.353	0.453	0.474	0.574	**BE28**	0.250	0.350	0.390	0.489

Table 10
Defuzzification of BE and conversion of CFP to BE probability.

	Defuzzification value	Probability value		Defuzzification value	Probability value
BE1	0.4459	0.0034	BE15	0.3002	0.0009
BE2	0.1803	0.0002	BE16	0.1763	0.0001
BE3	0.3893	0.0021	BE17	0.1489	0.0001
BE4	0.2671	0.0006	BE18	0.4726	0.0041
BE5	0.5462	0.0069	BE19	0.1751	0.0001
BE6	0.2930	0.0008	BE20	0.3203	0.0011
BE7	0.4900	0.0047	BE21	0.3203	0.0011
BE8	0.3026	0.0009	BE22	0.6978	0.0182
BE9	0.4960	0.0049	BE23	0.5642	0.0077
BE10	0.4227	0.0028	BE24	0.3139	0.0010
BE11	0.2511	0.0005	BE25	0.2839	0.0007
BE12	0.4854	0.0045	BE26	0.5198	0.0057
BE13	0.6087	0.0103	BE27	0.4642	0.0039
BE14	0.4636	0.0038	BE28	0.3696	0.0018

failure of the hydraulic pump/motor. The calibration of the rudder angle transmitter should be checked in every drydock as this would misguide the captain and create a risk of severe collision or grounding. It should be also noted that the good working condition of emergency generators should be ensured during onboard inspections as that might also increase the loss of steering ability in case the main power supply is somehow lost. The conditions of the propeller and flow arrangements should be carefully checked for cavitation and corrosion. Replacement of the equipment should be considered if there have major damages. The results also indicate that even though strict regulations and inspections have been carried out by port authorities and class societies for testing the recognition of all crew members onboard to emergency steering procedures, the high probability rate of the lack of crew's knowledge can still be observed, which indeed should have been as close as to zero to achieve a significant reduction in the probability of steering gear control failures. This situation brings into light that regular training of crew members should not be ignored and the documented safety management procedures of the company should be fulfilled. In addition, the ship crew should be encouraged to carry out the onboard drills in realistic scenarios. All the suggestions presented above will contribute to enhancing the safety and reliability of ship steering systems and reducing the risk of accidents caused by the loss of steering ability.

6. Conclusions

FTA is a powerful risk analysis method in which probability calculations are performed by determining the root causes of an undesired event. FTA is frequently favored due to its numerous advantages, such as its simple application and understandable graphical display. The traditional FTA method does not work if there is insufficient information on

Table 11
The occurrence probabilities of each MCS and sensitivity analysis.

Rank	MCS	Probability	FV-I	Rank	MCS	Probability	FV-I
1	BE13	1.03E-02	0.2075	17	BE22&BE23	1.41E-04	0.0028
2	BE5	6.87E-03	0.1384	18	BE19	1.39E-04	0.0028
3	BE9	4.86E-03	0.0979	19	BE22&BE26	1.04E-04	0.0021
4	BE7	4.66E-03	0.0939	20	BE17	7.68E-05	0.0015
5	BE12	4.50E-03	0.0907	21	BE22&BE27	7.01E-05	0.0014
6	BE18	4.11E-03	0.0828	22	BE22&BE28	3.24E-05	0.0007
7	BE14	3.84E-03	0.0774	23	BE22&BE24	1.88E-05	0.0004
8	BE10	2.80E-03	0.0564	24	BE22&BE25	1.34E-05	0.0003
9	BE3	2.12E-03	0.0427	25	BE21&BE23	8.55E-06	0.0002
10	BE20	1.10E-03	0.0222	26	BE21&BE26	6.34E-06	0.0001
11	BE8	9.14E-04	0.0184	27	BE21&BE27	4.26E-06	0.0001
12	BE15	8.89E-04	0.0179	28	BE21&BE28	1.97E-06	0.0000
13	BE6	8.20E-04	0.0165	29	BE21&BE24	1.14E-06	0.0000
14	BE4	6.01E-04	0.0121	30	BE21&BE25	8.14E-07	0.0000
15	BE11	4.87E-04	0.0098	31	BE1&BE2	5.19E-07	0.0000
16	BE16	1.42E-04	0.0029				

the probability of the occurrence of basic events that create an undesired top event. In these cases, using a fuzzy method helps to overcome this problem. Linguistic evaluations performed by problem experts can be converted into probability values with a scientific methodology. Consequently, it is simple to calculate the probabilities related to the top event and MCSs by considering the constructed tree.

In this study, the loss of ship steering ability was investigated. The root causes of the situation were investigated and a comprehensive tree was built. Since it is not possible to obtain information about the probability of occurrence of basic events, the probability of occurrence of events related to a fuzzy-based approach was calculated. As a result of the analyzes carried out in light of this information, the probability of the top event occurring was 4.86E-02. When all the findings are combined and analyzed, "steering gear hydraulic power failure" has the highest occurrence probability among the three main events that cause loss of steering ability, followed by "rudder failure" and "steering gear control failure", respectively. Another important contribution of the study to the literature is the determination of all MCSs and the calculation of their contribution to the top event. It was discovered that "oil leaking through sealings to surrounding" was the riskiest event. The combination of a main power supply failure plus an emergency power supply failure has the lowest occurrence probability among MCSs.

Although FFTA is a powerful and popular method in the literature, it also has some limitations. Firstly, data are required for the probability of events occurring in the system being analyzed in the FFTA method, and these data are obtained from field experts. Therefore, the data collection process can be challenging and time-consuming. In addition, FFTA is more complex than traditional fault tree analysis due to the need to use fuzzy logic and associated calculations, which requires significant computational resources and time for large and complex systems. During the construction of the fault tree, straits or narrow channels were not taken into account. It should be noted that the loss of steering ability on marine vessels is not a direct cause of an accident, but some other factors must also take place in the plot, e. g, proximity to shore, miscommunication with the engaged vessel, unfavorable wind, tide, and current conditions. All of these factors represent the limitations of the study.

CRediT authorship contribution statement

Samet Gürgen: Conceptualization, Methodology, Software, Writing – original draft. **Devran Yazir:** Conceptualization, Writing – review & editing. **Olgun Konur:** Conceptualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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