Establishing Role of Human Behaviour in Maritime Accidents Using Fuzzy Fault Tree Analysis

Ali Zaib* and Jingbo Yin

Abstract—**Human errors have played a crucial role in the occurrence of accidents in maritime industry. Numerous methods have been applied and tested to pinpoint the cause of accidents but due to lack of available data it is often difficult to pinpoint the root cause. In this paper, fuzzy fault tree analysis (FFTA) is applied in order to determine probability of human errors as well as its contribution in the cause of accidents. For that purpose, a real-life accident of M/T Zarga case is analyzed which happened while docking of ship in 2015 on South Hook Terminal, Wales, and United Kingdom which caused a serious injury to one of the crew members.**

Index Terms—**Maritime Transportation, risk analysis, accidental model, Human errors, fuzzy fault tree analysis (FFTA)**

I. Introduction

In a report by "Maritime Transportation Research Board of USA", the role of human factors in marine sector is defined as "the commission or omission of acts by maritime personnel that cause or contribute to merchant marine casualties or near-casualties" [1]. Human errors have contributed a lot in accidents involving maritime transportation. This is because even in this day and age of technological advancement some of the pedantic ship operations during transportation rely on human involvement. In a report by insurance company "Allianz Global Corporate & Specialty (AGCS)" in 2017, they reported that "Human error has long been regarded as a major cause of incidents in the shipping sector. It is estimated that about 75% to 96% of marine accidents can be attributed to human error." There were over 100,000 insurance claims out which 14,828 were of maritime sector [2].

Some of the previous work done to establish the role of human errors in accidents is included in this paper. The goal is to find out the quantitative impact by human errors in the occurring of maritime accidents so that they can be eliminated by ensuring proper methods and precautions that should be taken to avoid the monetary and human loss that results from the incident.

There has been a lot of work done to establish the role of human errors in maritime accidents. The authors of [3] used "Card Sorting Approach" to categorize the human errors contributing in marine calamities. The authors of [4] investigated the contribution of human errors by using semi-supervised Hierarchical methods. The authors of [5] used type-2 fuzzy SLIM method to foresee the human errors that can cause accidents during maritime transportation. A lot of research has been done including different accidental models to determine Human contribution in maritime accidents. This paper applies FFTA model to establish the quantitative and qualitative input made by human mistakes in the maritime industry accidents. It consists of the following parts, the current part contains the introduction and literature review, 2nd part contains methodology of the model, 3rd contains the analysis done on a real life accident case study and sheds lights on the results and conclusion of this research.

II. Methodology

The model used for analysis is Fuzzy fault tree analysis (FFTA). FFTA model is applied since it provides the information about the potential reason of the incident. Due to lack of data in maritime industry, it is difficult to pinpoint the actual cause of the accident, for that purpose, experts provide their opinion and possibility about the events. Fuzzy sets from FFTA model work on those verbal possibilities and convert them into probabilities, which are quantitative values that the model uses to find the results. Fuzzy set theory helps in obtaining expert judgment as it is in original language as semantic values [6–9]. FFTA is performed in following steps.

A. Making FT Diagram

First step is constructing the Fault tree (FT) diagram after establishing Top Event (TE). It is connected with other events that lead to the TE using logic gates and describes the relation between the events and their impact on the top event.

B. Converting Linguistic Values into Possibilities

Linguistic terms are obtained from the opinion of the marine experts. This is done due to lack of data available in maritime industry. They provide their verbal prediction about the possibility of each basic event (BE). Each expert's opinion about each event is different and each opinion is prioritized upon the relative experience (Sea and Shore time experience), Rank, Education and professional position. Table I shows assessment values of diverse experts [10]. A method was introduced which helped in deriving Fuzzy numerical values from the verbal opinion of set of heterogeneous experts and is called Similarity Aggregation Method (SAM) [9, 11]. It is used in the order described below.

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TABLE I: ASSESSMENT VALUES OF DIVERSE EXPERTS

Position	Ship master	5
	Pilot	4
	Academician	3
	Chief officer	2
	Junior officer or below	1
Serivce time (sea)	16 yrs or higher	5
	11 to 15 yrs	4
	6 to10 yrs	3
	3 to5 yrs	2
	Less than 2 yrs	1
Education	PHD	5
	Masters	4
	Bachelors	3
	HND	2
	School level	1
Service time(shore)	20yrs or higher	5
	15 to 19 yrs	4
	10 to 14 yrs	3
	6 to 9 yrs	2
	Less than 5 yrs	1

C. Aggregating Obtained Possibilities

In this step, imagine every expert, $E_k(k = 1,2,\ldots M)$ shows his / her views about specific trait with respect to certain environment by an anticipated set of verbal parameters. That is then altered into fuzzy digits. Concept of this method is described below [10, 12].

D. Calculating Degree of Agreement

Degree of agreement of experts is obtained with the help of following equation:

$$S(\tilde{X}, \tilde{Y}) = 1 - \frac{1}{4}\sum_{i=1}^{4}|x_i - y_i| \quad (1)$$

Where $S(\tilde{X}, \tilde{Y})$ represents similarity function and $S(\tilde{X}, \tilde{Y}) \in [0,1]$

E. Average Agreement (AA)

Average agreement (AA) is obtained through applying the following formula

$$AA(E_x) = \frac{1}{N-1}\sum_{x\neq y}^{N} S(\widetilde{Q_x} - \widetilde{Q_y}) \quad (2)$$

F. Relative Agreement (RA)

Relative Agreement of the experts is determined by following equation:

$$E_x(x = 1.2, \ldots N) \ where \ RA(E_x) = \frac{A(E_x)}{\sum_{x=1}^{N} A(E_x)} \quad (3)$$

A. Consensus Coefficient (CC)

Consensus coefficient (CC) of the experts is calculated by using the following formula:

$$E_x(x = 1,2, \ldots, N)$$

where $CC(E_x) = \alpha.\gamma(E_x) + (1-\alpha).RA(E_x)$ (4)

G. Aggregate results of possibilities

Aggregated results of expert's opinion (AGG) can be obtained by Eq. (5)

$$\tilde{S}(AGG) = B(Exp_1) \times \tilde{Q}1 + B(Exp_2) \times \tilde{Q}2 + \ldots, +B(Exp_N) \times \tilde{Q}N \quad (5)$$

H. Defuzzifying of Fuzzy possibility

In order to get a solid value Defuzzifying is necessary of the expert judgments. This is done by the following equation:

$$Y^* = \frac{\int V_i(y)ydy}{\int V_i(y)} Y^* = \frac{\int V_i(y)ydy}{\int V_i(y)} \quad (6)$$

- Where Y* represents fuzzy possibility
- $V_i(y)$ shows aggregated membership function
- Y denotes output variable

I. Converting possibilities into probabilities

Eqs. (7) and (8) were used by [13] to convert fuzzy failure possibility to fuzzy failure probability. Fuzzy probability rate (FPT) can be taken from fuzzy possibility rates (FPs) [13]. The equations are as follows:

$$Pr = \begin{cases} \frac{1}{10^k}, & Fp_s \neq 0 \\ 0, & Fp_s = 0 \end{cases} \quad (7)$$

$$K = \left[\left(\frac{1-FPs}{FPs}\right)\right]^{1/3} \times 2.301 \quad (8)$$

J. Calculating TE Probability using Minimal Cut Sets (MS)

Eq. (9) shows MS

$$TE = MS_1 + MS_2 + \cdots + MS_M = \cup_{i=1}^{m_c} MS \quad (9)$$

In case of independent MS the following equation is applied to establish the probability of TE.

$$P(TE) = P(MS_1 \cup MS_2 \cup \ldots \cup MS_M) = P(MS_1) + P(MS_2) + \cdots P(MS_M) - (P(MS_1 \cap MS_2) + P(MS_1 \cap MS_3) + \ldots P(MS_i \cap MS_j) \ldots) \ldots + (-1)^{M-1} P(MS_1 \cap MS_2 \cap \ldots \cap MS_M) \quad (10)$$

K. Classification of Minimal Cut Sets (MS)

To rank MS's, Vesely–Fussell Importance Measure (V–FIM) [7]. The classification is done by the Eq. (11)

$$I_j^{VFM}(y) = \frac{P_j(y)}{P_k(y)} \quad (11)$$

III. Analysis & Results

To apply this method, a real life case study was selected. The accident analyzed for this purpose is of M/T Zarga that happened on the South Hook Terminal in 2015. An Officer in charge was hit in the head by the broken forward mooring rope and was seriously injured. The ship was loaded with 266,000 m^3 of Liquid nitrogen gas [14, 15].

A group of five experts, two masters, two academians and a pilot participated in a survey to help establish the basic events (BE) and their possibilities in related to the accident. The TE of the event is Rope failure, which caused the accident. All the experts have relative experience in maritime transportation. Table II contains the relative profile of each expert.

TABLE II: Expert Profile

professional position	sea service time	shore service time	education level
Master	12	11	M.Sc.
Master	7	6	Bachelor
Academician	6	9	PhD
Academician	3	4	M.Sc.
Pilot	4	4	bachelor

Top Event (TE) is main event that has to be removed in order to avoid the damage caused by the incident. In this particular case study the rope failure at forward mooring line that hit the officer incharge in the head and caused a severe injury. After establishing the TE, Fault tree (FT) diagram is established in accordance with experts' opinion. Fig. 1 shows Fault tree diagram, which contains the connection between the basic events and the TE.

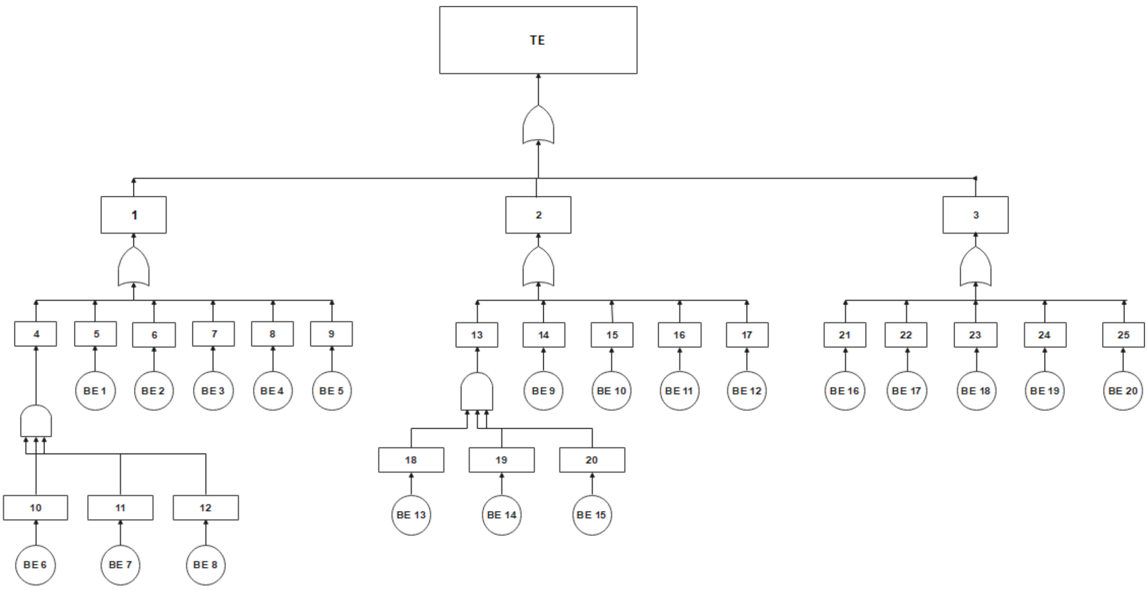

Fig. 1. Fault tree diagram.

TABLE III: List of Events

S.No.	Description	Operational faults
1	TE	Rope Failure resulting in severe head injury
2	IE	Incorrect Planning and execution
3	IE	Technical Faults
4	IE	Not following proper instructions
5	BE1	Early release of tugs
6	BE2	OIC and Bosun doing mooring operations instead of recalling mooring crew
7	BE3	Lack of Experience of OIC and Bosun
8	BE4	OIC was Fatigued
9	BE5	Not replacing overused and weakened mooring ropes by shipping company
10	BE6	Changing the standard mooring ropes configuration on last day
11	BE7	forward mooring crew not rectifying the spring lines configuration while backward did
12	BE8	OIC not following the instructions given by the Master of the ship
13	IE	Improper mooring method application
14	BE9	Not considering the weather conditions upon berthing
15	BE10	Using forward spring line to move the ship in position instead of recalling the tugs

16	BE11	Changing the mooring ropes configuration provided by the company guidelines
17	BE12	Not ensuring the instructions given by the master of the ship were implemented
18	BE13	Not using proper mooring ropes
19	BE14	Standing in snap back zone during mooring operation
20	BE15	Improper tug assistance
21	BE16	Using Weakened Mooring ropes
22	BE17	Over tensioning of mooring ropes
23	BE18	Port authority not providing assistance to check the tension of the ropes
24	BE19	Using round rope propeller
25	BE20	Non authorized crew on mooring operations

There are twenty basic and 5 intermediate events established by the experts. The description of each event is in Table III. These events are in descriptive form and due to lack of data in marine sector; fuzzy sets are used to attain rate of failure [9]. It is possible to transform these verbal opinions into fuzzy values [16]. Table IV shows the set of fuzzy number in relation to the vocal values that explains the likelihood of each incident [17].

A numerical estimation system was introduced where systematized seven verbal scales were used {Very Low (VL), Low (L), Mildly Low (ML), Medium (M), Mildly High (MH), High (H) and Very High (HV)} [17]. Table V contains the weighting factor and score of each expert according to their relative experience.

TABLE IV Linguistic Terms & Values

Linguistic term	Fuzzy numbers
Very low (VL)	(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)

TABLE V: Marine Expert Weights

weighting factor				TW	weighting score
5	4	3	4	16	0.26
5	3	2	3	13	0.21
3	3	2	5	13	0.21
3	2	1	4	10	0.16
4	2	1	3	10	0.16

Experts have their own opinion about each basic event and their occurrence possibility. Table VI shows the verbal opinions of the experts regarding potential of each B.E. After obtaining the possibility of each event, probability of each event has to be obtained. In order to obtain that, first aggregation of each event is achieved. Since there are twenty determined basic events, for representation only BE1 is used. Eqs. (1) to (4) are used for this purpose. Table VII illustrates the similarity function and its value of each expert. Table VIII shows the Relative agreement (RA), Average agreement (AA) and consensus coefficient (CC) of marine experts on BE1. According to the authors of [17], all the specialists are assumed similar, so α is equal to 0.5. Thereafter, aggregate of the judgments of expert is obtained by using Eqs. (5) and then (6) is used to convert those combined values into hard values. Table IX contains the aggregated possibilities of specialist's opinion and result possibilities of each Basic Event.

TABLE VI: Verbal Possibility of Each Basic Event according to Experts

	M.Exp1	M.Exp2	M.Exp3	M.Exp4	M.Exp5
BE1	VH	VH	H	MH	MH
BE2	H	H	M	MH	M
BE3	ML	M	ML	L	L
BE4	L	L	VL	L	VL
BE5	H	MH	MH	M	M
BE6	MH	M	MH	M	M
BE7	VH	H	VH	H	H
BE8	VH	VH	H	MH	H
BE9	MH	M	ML	M	ML
BE10	H	MH	MH	M	M
BE11	M	M	ML	L	L
BE12	ML	ML	L	M	M
BE13	VH	VH	H	H	H
BE14	MH	MH	H	MH	VH
BE15	VH	H	H	MH	VH
BE16	M	M	ML	M	ML
BE17	L	ML	L	L	ML
BE18	L	VL	L	L	VL
BE19	VL	VL	VL	VL	VL
BE20	H	H	M	ML	M

TABLE VII: Similarity Function Values

SIMILARITY FUNCTION		
1	S(E1&E2)	1.00
2	S(E1&E3)	0.70
3	S(E1&E4)	0.85
4	S(E1&E5)	0.70
6	S(E2&E3)	0.70
7	S(E2&E4)	0.85
8	S(E2&E5)	0.70
10	S(E3&E4)	0.85
11	S(E3&E5)	1.00
12	S(E4&E5)	0.85

TABLE VIII: AA, CC & RA VALUES FOR BE1

M. Exp.	Average Agreement (AA)	Relative Agreement (RA)	Consensus coefficient (CC)
1	0.665	0.199	0.229
2	0.665	0.199	0.204
3	0.690	0.207	0.208
4	0.660	0.198	0.179
5	0.660	0.198	0.179

TABLE IX: AGGREGATED POSSIBILITIES OF SPECIALIST'S OPINION AND POSSIBILITIES OF BE'S

Basic Events	Probabilities obtained from possibilities
BE1	3.51×10^{-2}
BE2	9.93×10^{-3}
BE3	1.16×10^{-3}
BE4	8.81×10^{-5}
BE5	1.17×10^{-2}
BE6	4.29×10^{-2}
BE7	5.18×10^{-2}
BE8	7.75×10^{-3}
BE9	4.18×10^{-3}
BE10	1.17×10^{-2}
BE11	1.64×10^{-3}
BE12	1.87×10^{-3}
BE13	5.18×10^{-2}
BE14	2.18×10^{-2}
BE15	4.20×10^{-2}
BE16	3.28×10^{-3}
BE17	5.28×10^{-4}
BE18	8.81×10^{-5}
BE19	5.66×10^{-6}
BE20	9.93×10^{-3}

TABLE X: PROBABILITIES OF EACH EVENT OBTAINED FROM EXPERT JUDGMENT

Basic events	Probabilities of failures obtained from possibilities
BE1	3.51×10^{-2}
BE2	9.93×10^{-3}
BE3	1.16×10^{-3}
BE4	8.81×10^{-5}
BE5	1.17×10^{-2}
BE6	4.29×10^{-2}
BE7	5.18×10^{-2}
BE8	7.75×10^{-3}
BE9	4.18×10^{-3}
BE10	1.17×10^{-2}
BE11	1.64×10^{-3}
BE12	1.87×10^{-3}
BE13	5.18×10^{-2}
BE14	2.18×10^{-2}
BE15	4.20×10^{-2}
BE16	3.28×10^{-3}
BE17	5.28×10^{-4}
BE18	8.81×10^{-5}
BE19	5.66×10^{-6}
BE20	9.93×10^{-3}

TABLE XI: MCS, OCCURRENCE PROBABILITY AND V-FIM VALUES

MCS	Occurrence probability	V–FIM
BE1	3.51×10^{-2}	0.38454
BE2	9.93×10^{-3}	0.10860
BE3	1.16×10^{-3}	0.01271
BE4	8.81×10^{-5}	0.00096
BE5	1.17×10^{-2}	0.12849
BE6BE7BE8	1.72×10^{-5}	0.00019
BE9	4.18×10^{-3}	0.04578
BE10	1.17×10^{-2}	0.12849
BE11	1.64×10^{-3}	0.01799
BE12	1.87×10^{-3}	0.02042
BE13BE14BE15	4.74×10^{-5}	0.00052
BE16	3.28×10^{-3}	0.03591
BE17	5.28×10^{-4}	0.00577
BE18	8.81×10^{-5}	0.00096
BE19	5.66×10^{-6}	0.00006
BE20	9.93×10^{-3}	0.10860

With the aim of achieving the probability of every incident, to obtain the value of TE and MCS's, Eqs. (9) and (10) are used. Table X contains the probabilities of each event converted from possibilities of all incidents. Keeping in mind the fault tree diagram and the logic gates representing the process, probability of TE is 9.20×10^{-2}. After that, Eq. (11) is applied to calculate the MCS's, their occurrence probability and V-FIM in Table XI.

From the Results of analysis, the probability of TE tells us high chance of accident occurring on the ship. The Events that have contributed in the accident occurring are BE1, BE2, BE5, BE10 and MCS of BE6BE7BE8 considering human errors that played a part leading to the accident. To eliminate the accident, the basic events and minimal cut sets with highest of probability have to be removed. From the events description, it is clear that these events happened due to negligence, lack of following chain of command, not considering proper methods of mooring during an extreme event and hasty decisions made due to an emergency.

IV. CONCLUSION

According to the analysis, it can be seen that Human errors contributed strongly in occurrence of the incident, which resulted in a severe injury of a person. However, these can be removed easily by making sure proper mooring methods are applied, chain of command and orders are followed, by making sure that each crewmember knows their roles in the operations and proper inspection is done prior to any maritime travel. In addition, it should be established that the crew members are to be made aware of and trained for certain weather conditions that can occur on their journey, this way these accidents can be avoided and will result in safer ship transportation in future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ali Zaib and Jingbo Yin identified the major factors, conceptualized and developed the model. Ali Zaib run the model, analyzed the results and wrote the manuscript. Jingbo Yin supervised the overall study. Both authors reviewed the manuscript.

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