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Collision Risk Modelling of Supply Vessels and Offshore Platforms Under Uncertainty

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Serious accidents in the marine and offshore industry have underscored the need for safety evaluation of maritime operations using risk and safety analysis methods which have become a powerful tool in identifying technical solutions and operational management procedures. Given that Fault Tree Analysis (FTA) is a known methodology used for analysing engineering systems, the approach is usually conducted using known failure data. But most offshore operations are conducted in a challenging and uncertain environment and the failure data of some of these systems are usually unavailable requiring a flexible and yet robust algorithm for their analysis. This paper therefore seeks to analyse the complex structure of Offshore Supply Vessel (OSV) collision with platforms by incorporating a Fuzzy Fault Tree Analysis (FFTA) method. Fuzzy set theory provides the flexibility to represent vague information from the analysis process. The methodology is structured in such a manner that diverse sets of data are integrated and synthesized for analysing the system. It is envisaged that the proposed method could provide the analyst with a framework to evaluate the risks of collision enabling informed decisions regarding the deployments of resources for system improvement.

KEYWORDS

1. Offshore. 2. Modelling. 3. Safety. 4. Ship.

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1. INTRODUCTION. Over the past few years, the growing demand for deep-water offshore operations and increasing maritime traffic has increased the risk of ships and offshore platform collision. Several incidents have been reported over these periods. For example, on the United Kingdom Continental Shelf (UKCS), supply vessel collisions with a platform have a rather high probability of occurrence, approximately 17 percent per platform in a year (Serco Assurance, 2003; Nouri et al., 2008).

The gas leak resulting from the *Mumbai High North* (MHN) disaster which occurred on 29 July 2005 led to ignition that set the platform on fire and killed 22 people (John, 2010).

Analysis of the accident revealed that strong swells pushed the Offshore Supply Vessel (OSV) towards the platform hitting the rear part of the vessel causing rupture of one or more of the platform's gas export risers leading to the accident. The collision probability between an OSV and parts of an offshore platform such as the flexible riser system is considered a significant contribution to major hazard risk in the oil and gas industry's operations.

In response to the MHN disasters in 2005, the UK Health and Safety Executive (HSE) has written to various operators on the UKCS asking them to review the riser integrity/protection standard and procedures on production installations for assurances that there is a very low risk of a similar incident in UK waters (John, 2010). The hydrocarbon risers on UK offshore installations are generally considered as Safety Critical Elements (SCEs) and are therefore subject to independent verification and assessment, hence the need for their integrity assessment.

Research by John (2010), Kvitrud (2011) and Oltedal (2012) has revealed that a significant number of offshore accidents associated with OSVs and platforms have occurred due to the challenging field of offshore operations, the multiplicity of stakeholders involved in the system and their operational complexity. Although most of the analysed accidents are minor, a few are termed major with catastrophic damage and long term economic consequence to operators of the facilities.

The aim of this paper is to propose a modelling approach for collaborative modelling of OSV collision with platforms during operations using the Fuzzy Fault Tree Analysis (FFTA) method. This has been organised as follows: Section 2 provides literature on offshore supply vessel operations, offshore risk assessment, risk parameters of OSV collision with platforms, and a modelling approach using Fault Tree Analysis (FTA) and FFTA. Section 3 explains the methodology of the study. Section 4 focuses on a case study to show how it can be applied. Finally, Sections 5 and 6 offer discussions and conclusion.

2. LITERATURE REVIEW

2.1. *Offshore Supply Vessel Operation (OSVO).* OSVOs are the main system of transportation to offshore platforms by using a Dynamic Positioning (DP) system for operations close to the platform. The DP system is a computer-controlled system that helps to automatically maintain the vessel's position by considering the effects of wind and currents (Kongsvik et al., 2011). Experience has shown that the DP system is usually not turned on during the voyage to the platform, but is prepared when approaching the 500-metre safety zone around the installation.

2.2. *Vessel's Voyage from Port to Installation.* Extensive voyage planning (including placement of cargo and route planning) must be undertaken before an OSV leaves the port to ensure safety and cost-effectiveness of their operations. Also, to reduce the probability of technical failures, it is important that testing of technical equipment on board the vessel is done at a regular interval to detect and repair latent errors that may lead to an accident.

2.3. *Surveillance of vessels around the 500-metre safety zone of installations.* A 500-metre safety zone around the offshore installation has been defined by safety analysts to be a circular area with a 500 metre radius from the platform. The purpose of the zone is to control traffic around the platform thereby reducing the number of potential collisions. The traffic around the safety zone is monitored from an onshore surveillance centre or in some cases from an offshore control tower. This surveillance is mostly directed towards passing vessels and other irregular traffic, but supply vessels sailing directly towards the platform will be contacted (ConocoPhillips, 2013; Tvedt, 2013).

2.4. *Vessels approaching safety zone of installation.* OSVs usually establish communication with the surveillance centre and installation approximately one hour before their arrival (Ali and Haugen, 2012). Permission to enter the safety zone must be sought from the installation, and permission cannot be granted until both vessel and installation have exchanged the pre-arrival checklist which is usually developed internally and includes checking for failures in technical equipment and clarifying responsibility on board the vessel.

2.5. *Offshore risk assessment.* Offshore risk assessment started in the late 1970s, with the utilisation of data from the nuclear power generation industry (Bai and Jin, 2016). However, following the *Alexander L. Kielland* accident in 1981 that resulted in the total loss of the platform and 123 fatalities, the Norwegian Petroleum Directorate (NPD) issued guidelines that required Quantitative Risk Assessment (QRA) to be carried out for all new offshore installations during the conceptual design phase (NPD, 1992). A further milestone was when Safety Case Legislation was developed in the UK following the *Piper Alpha* accident that resulted in total loss of the platform and 165 fatalities in 1988 (UK HSE, 1992; 1995).

Several types of offshore risks exist, these are structural and marine events, collisions, fires, dropped objects, blowouts, riser/pipeline leaks, process leaks and transport accidents, among others. The focus of this study is on collision risk which is discussed as follows.

2.6. *Collision Risk.* Ship/platform collision is one of the main risk contributors in offshore exploration and production activities. The most frequently occurring collisions are the impacts between OSVs and platforms and the collision risks still have major hazard potential. In most situations, this type of collision only causes minor damage to platforms. Based on literature review, major ship/platform collision accidents have different chains of events when analysing their risks than the areas the QRAs in use today take into account (Tvedt, 2013; Oltedal, 2012; Kvitrud, 2011).

2.7. *Analysis of some OSV collision accidents with installations.* The review of accidents such as the *Far Symphony* collision with *West Venture Semi* in 2004, the *Mumbai High North* (MHN) disaster, the *Indian Ocean Carrier* collision with the bridge at Ekofisk in 2005, the *Bourbon Surf* collision with *Grane Jacket* in 2007, Supply Vessel collisions with drilling rigs in 2009 (Ship Owners, 2015; Tvedt, 2013; Oltedal, 2012; Kvitrud, 2011; John, 2010) have revealed that the risks associated with the OSV collision and installations are multifaceted. It can be observed that the primary causes of the accidents have many similarities but the whole chain of events and the underlying factors have many differences. To enable the use of a flexible risk analysis technique, the information available must be structured. For this paper, a specific model is constructed based on the identified risk factors as presented in Table 1. These risk factors are chosen because they are regarded as the most significant ones associated with the accident. The selection of such risk factors or parameters is based on extensive discussions with experts and a robust literature review (John, 2010 and Bai and Jin, 2016).

2.8. *Modelling using Fault Tree Analysis (FTA).* In the conventional approach to solving the Fault Tree (FT), probability theory is used. The crisp values of the Basic Events' (BEs') probabilities must be known. It is usually assumed that the basic events in FTs are independent and could be represented as probabilistic numbers (Trbojevic and Carr, 2000).

Table 1. Risk Factors Associated with Specific Model.

S/No	Risk Factors	S/No	Risk Factors
1	Boost lines failure	9	Ship collision
2	Failure of thrusters	10	Blowout
3	Human error	11	Corrosion
4	Extreme weather	12	Connection leak
5	Loss of position	13	Fatigue
6	Subsea collision	14	Kill and choke lines failure
7	Dropped object	15	Navigational aids failure

In the case where the FT for the Top Event (TE) contains only one independent basic event that appeared in the tree construction, the TE probability can be obtained by working the BE probabilities up through the tree (Andrews and Moses, 2002). The intermediate gate events (AND or OR) probability can be calculated by working from the bottom of the tree upward until the TE probability is obtained. The "AND" probability is obtain using Equation (1).

$$P = \prod_{i=1}^{n} P_i \tag{1}$$

where P stands for the occurrence probability of TE, P_i stands for the failure probability of BE i. n stands for the number of basic events associated with the "AND" gate. In the case of the "OR", Equation (2) is used to obtain the probability.

$$P = 1 - \prod_{i=1}^{n} (1 - P_i) \tag{2}$$

where P stands for the probability of the TE, P_i stands for the occurrence probability of BE i, n stands for the number of BEs associated with the "OR" gate.

If a FT has many BEs in the tree, the probability of the TE can be obtained by utilising Minimal Cut Sets (MCS). The MCS is the collection of the smallest BEs such that if all the BEs occurred, the TE event will definitely occur. If these BEs are prevented from happening, the TE of the system will not happen. If a FT has MCSs which are represented by MC_i, $i = 1, 2, \ldots . n_c$, then the TE (T) exists if at least one MCS exists (Andrews and Moses, 2002).

$$T = MC_1 + MC_2 + \cdots + MC_{nc} = \bigcup_{i=1}^{nc} MC_i \tag{3}$$

The exact evaluation of the TE happening can be obtained by:

$$\begin{aligned} P(T) = P(MC_1 \cup MC_2 \cup \ldots . \cup MC_N) = P(MC_1) + P(MC_2) + \ldots P(MC_N) - (P(MC_1 \cap MC_2) \\ + P(MC_1 \cap MC_3) + \cdot \cdot P(MC_i \cap MC_j) \ldots) \cdot \cdot + (-1)^{N-1} P(MC_1 \cap MC_2 \cap \ldots \cap MC_N) \end{aligned} \tag{4}$$

where $P(MC_i)$ is the occurrence likelihood of MC_i and N is the number of MC.

2.9. *Fuzzy Fault Tree Analysis.* For the past five decades FTA has been used as a powerful technique in the analysis of risks. FTA is a logical and diagrammatic technique used to systematically estimate system safety and reliability by means of qualitative and quantitative methods (Lavasani et al., 2012; Uğurlu et al., 2015). The application of FTA requires the failure probability of failure events. However, it is often difficult to obtain failure probabilities of some past events or historical accidents. This is because of the ever-dynamic nature of the environment and the high levels of uncertainty associated with engineering systems (Mentes and Helvacioglu, 2011). Furthermore, failure probabilities of components are considered as exact values in which the failure probabilities must gain either full membership or no membership. This method has difficulty in obtaining failure probabilities of components due to the unavailability of sufficient failure data. Moreover, the imprecision or vagueness in failure data may render the overall result questionable (Flage et al., 2013). To overcome this challenge in the application of FTA, it is necessary to incorporate experts' judgement to obtain rough estimates of failure data. However, the obtained failure possibilities from experts cannot be used directly as failure probabilities or exact failure rates to carry out risk assessment of engineering components. This is because these estimates contain some level of imprecision or vagueness, therefore Fuzzy Fault Tree Analysis (FFTA) is adopted to deal with such imprecisions and ambiguity arising from experts' judgement and to translate the linguistic values into exact failure rates that can be used to evaluate system safety and reliability (Uğurlu et al., 2015). This research aims to extend the application of FFTA to evaluating collision risk during ship and platform interface under uncertainty.

3. METHODOLOGY.

The proposed framework provides the flexibility needed by experts to represent vague information resulting from the lack of quantitative data using experts' opinions. The framework is itemised in the following steps and presented in Figure 1 as derived from the existing literature (John et al., 2016; 2015; John, 2010; 2013):

(1) Preliminary system analysis phase.
(2) Selection of experts.
(3) Estimating weights of experts.
(4) Rating phase.
(5) Aggregation phase.
(6) Defuzzifying state.
(7) Converting fuzzy possibilities scores to fuzzy failure probabilities.
(8) Estimation of minimal cut sets.
(9) Ranking of minimum cut sets.

3.1. *Preliminary System Analysis (Step 1).*

This section analyses offshore operations and obtains relevant information through a robust literature review and discussion with the domain experts involved with the operations of OSV and platforms. As a consequence, a specific model for OSV collision with platform is developed (Figure 2).

3.2. *Selection of Experts (Step 2).*

Complete impartiality of expert knowledge is often difficult to achieve when carrying out an assessment of a complex system due to individual perspectives and goals (Trbojevic and Carr, 2000). Based on John et al. (2016), criteria to identify experts are based on the person's period of learning, field experience and analytical behaviour in a specific domain of knowledge, thus influencing his or her judgment, and the specific circumstances of the heterogeneous group of expert.

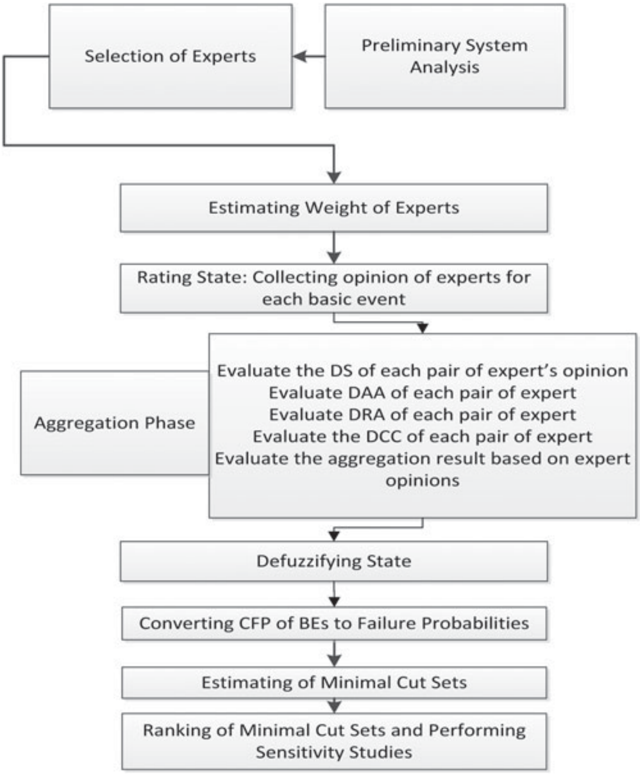

Figure 1. Flow Chart of the Proposed Methodology.

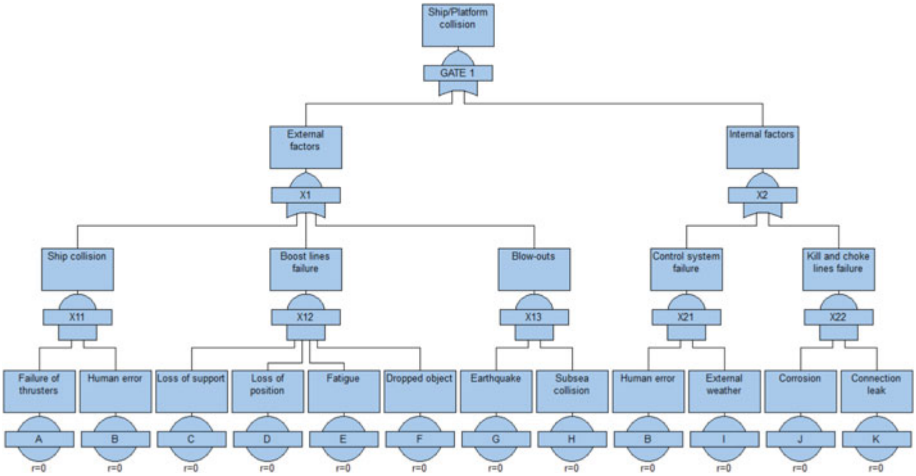

Figure 2. A specific model for OSV collision with a platform.

3.3. *Estimating Weights of Experts (Step 3).* In line with the modelling approach presented by Yuhua and Datao (2005), this phase of the analysis deals with the calculations of experts' weights, which are determined using the Delphi method. As an example, if an expert is more experienced and 'better' than others due to his or her knowledge proficiency during a group decision making session, he or she is given a greater score. Accordingly, the weight of the expert can be determined in a simplified manner. For instance, let $\mathbf{E_1}$, $\mathbf{E_2}$, $\mathbf{E_3} \ldots \mathbf{E_n}$, be scores of experts, Based on Equations (5) and (6), the weighting score and factor of experts can be determined as:

$$\text{Weight score of } E_i = \text{IP score of } E_i + \text{ST score of } E_i + \text{AQ score of } E_i + \text{Age of } E_i \quad (5)$$

where IP stands for industrial position, ST and AQ represent service time and academic qualification of the domain experts respectively as shown in Table 2.

$$\text{Weight factor of } E_i = \frac{\text{Weight score of } E_i}{\left(\sum_{i=1}^{n} \text{Weight score of } E_k\right)} \quad (6)$$

3.4. *Rating State (Step 4).* This phase provides experts with the flexibility of expressing their opinion on each basic event due to insufficient data using sets of linguistic variables. The linguistic variables are convenient in dealing with circumstances that are complex or ill-defined to be described quantitatively. Fuzzy Set Theory (FST) is well suited for modelling such subjective linguistic variables (Pillay and Wang, 2003). Due to their easiness of use, trapezoidal fuzzy numbers are usually used for this analysis by the experts based on a common interval [0, 1]. In FST, conversion scales are applied to transform the linguistic terms of experts into fuzzy numbers for system modelling and analysis. In line with the conversion scale proposed by Chen and Hwang (1999), this study adopts a similar approach for the experts' rating where both the performance score ($\mathbf{x}$) and the membership degree ($\boldsymbol{\mu}(\mathbf{x})$) are in the range of 0 and 1 as shown in Figure 3.

3.5. *Aggregating state.* Since each of the experts will have a different opinion based on his experience and expertise, it becomes imperative to combine or aggregate their opinion into a consensus to have a single value that can be used in the risk assessment process.

In line with the modelling approach presented by Hsu and Chen (1994), where a heterogeneous/homogeneous group of experts are used, consider that based on their expertise, each expert E_r $(r = 1, 2, 3, \ldots m)$ expresses his/her opinion on a particular criterion by a set of linguistic variables which are described by fuzzy numbers. The aggregation of the experts' judgement can be obtained as follows:

1. Calculate the degree of agreement (degree of similarity) $S_{uv}(\check{\delta}_u \check{\delta}_v)$ of the opinions $\check{\delta}_u$ and $\check{\delta}_v$ of a pair of experts E_u and E_v where $S_{uv}(\check{\delta}_u \check{\delta}_v) \in (0, 1)$. Based on this approach, $\tilde{X} = (a_1, a_2, a_3, a_4)$ and $\tilde{Y} = (b_1, b_2, b_3, b_4)$ are trapezoidal fuzzy numbers. The degree of similarity between these two fuzzy numbers can be evaluated by the similarity function S defined as follows (Hsu and Chen, 1994):

$$S(\tilde{X}, \tilde{Y}) = 1 - \frac{1}{4} \sum_{i=1}^{4} |a_i - b_i| \quad (7)$$

where $S(\tilde{X}, \tilde{Y}) \in (0, 1)$. It is important to mention that the larger the value of $S(\tilde{X}, \tilde{Y})$, the greater the similarity between two fuzzy numbers of $\tilde{X}$ and $\tilde{Y}$ respectively.

Table 2. Weighting Scores and Constitution of Different Experts.

Constitution	Classification	Score
Industrial Position (IP)	Operations Manager	5
	Master Mariner	4
	Chief Engineer	3
	Port Pilot	2
	Others	1
Service Time (ST)	$>$ 30 years	5
	20-29	4
	10-19	3
	6-9	2
	$<$ 5 years	1
Academic Qualification (AQ)	PhD	5
	Master	4
	Bachelor	3
	HND/OND	2
	School Leaver	1
Age	$>$ 50	5
	40-49	4
	31-39	3
	20-30	2
	$<$ 20	1

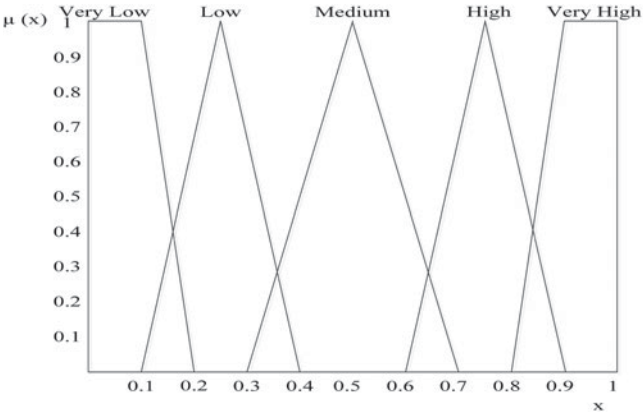

Figure 3. Membership functions of experts' opinion, source (Chen and Hwang, 1999).

2. Calculate the degree of Average Agreement (AA) of expert E_u; this can be obtained as follows:

$$AA(E_u) = \frac{1}{N-1} \sum_{\substack{u \neq v \\ v=1}}^{N} S(\check{\delta}_u, \check{\delta}_v) \tag{8}$$

3. Calculate the Relative Agreement (RA) degree $RA(E_u)$ of the experts; This can be obtained as follows:

$$RA(E_u) = \frac{AA(E_u)}{\Sigma_{u=1}^{N} AA(E_u)} \tag{9}$$

4. Calculate the Consensus Coefficient degree CC of expert E_u $(u = 1, 2, \ldots M)$; this can be analysed as follows:

$$CC(E_u) = \beta \times w(E_u) + (1 - \beta) \times RA(E_u) \tag{10}$$

   where $\beta (0 \leq \beta \leq 1)$ is a relaxation factor of the proposed approach, it highlights the importance of expert's weight $(w(E_u))$ over $RA(E_u)$. It is important to note that when $\beta = 0$, no importance has been given to the weight of experts and, thus a homogeneous group of experts is used. When $\beta = 1$, then the consensus degree of an expert is the same as his or her importance weight. The consensus coefficient degree of each expert is a good measure for evaluating the relative worthiness of judgement of all experts participating in the decision making process (Lavasani et al., 2012). It is the responsibility of the decision maker to assign an appropriate value of β. β is considered to be 0·75 in this study because the degree of importance of each decision maker is more important than his/her relative agreement degree.
5. The expert aggregated judgement $\tilde{R}_{AG}$ can be obtained as follows:

$$\tilde{R}_{AG} = CC(E_1) \times \tilde{R}_1 + CC(E_2) \times \tilde{R}_2 + \cdots + \cdots CC(E_N) \times \tilde{R}_N \tag{11}$$

   where $\tilde{R}_i (i = 1, 2, \ldots N)$ is the subjective rating of a given criterion with respect to alternative from experts.

3.6. *Defuzzification Phase (Step 6).* Defuzzification is an inverse method used to transform the output from the fuzzy domain back into the crisp domain to produce a quantifiable result in the fuzzy logic. To rank the minimal cut sets, all aggregated fuzzy numbers must be defuzzified. Due to its ease of use when compared to other techniques such as that suggested by Hsu and Chen (1994), the Centre area defuzzification technique proposed by Sugeno (1999) is used in this analysis. Each element of matrix $\mathbf{\tilde{x}_i} = (\mathbf{a_1}, \mathbf{a_2}, \mathbf{a_3}, \mathbf{a_4})$ can be converted to a crisp value using Equation (12).

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} x dx + \int_{a_2}^{a_3} x dx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} x dx}{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} dx + \int_{a_2}^{a_3} dx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} dx} = \frac{1}{3} \frac{(a_4 + a_3)^2 - a_4 a_3 - (a_1 + a_2)^2 + a_1 a_2}{a_4 + a_3 - a_1 - a_2} \tag{12}$$

3.7. *Converting Fuzzy Possibilities Scores to Fuzzy Failure Probabilities (Step 7).* When converting fuzzy possibilities to fuzzy failure probabilities, it is important to keep the same unit (e.g. occurrence probability with a period of time set). Since the data obtained for this analysis are subjective in nature, this needs to be converted to fuzzy failure probabilities to be used in the fault tree software. In line with the modelling approach presented in Yuhua and Datao (2005), this research adopts a similar approach for converting fuzzy possibility scores to fuzzy failure probability score.

$$F\,\mathrm{Pr} = \begin{cases} \dfrac{1}{10^k} & FPs \neq 0 \\ & FPs = 0 \end{cases} \tag{13}$$

where,

$$K = \left[\frac{(1 - FPs)}{FPs}\right]^{(1/3)} \times 2{\cdot}301 \tag{14}$$

3.8. *Estimation of Minimal Cut Sets (Step 8).* Cut sets are sets of system events that lead to the failure occurrence of the system. MCS are an irreducible path that leads to the occurrence of an undesirable event or TE. For the TE to occur, all the failure events in the MCS must happen. One-component MCSs represent the single failure event that will cause the TE, while two-component MCSs represents double failures that will happen together to cause the failure of the TE (Lavasani et al., 2012). In light of the above, the TE can be obtained from the MCS by using Equation (3).

3.9. *Ranking of Minimal Cut Sets (Step 9).* The calculation of MCS is of importance in FTA. This process is used to determine the contribution of each MCS to the occurrence probability of the TE. The ranking serves as significant information for obtaining the required information of basic events with a high contribution to the probability of the TE. Analysis of literature revealed various methods used in ranking MCSs. The most widely used in literature is the Fussell-Vesely Measure of Importance (F-VIM). It is the contribution of the MCSs to the TE probability. F-VIM is determinable for every MCSs modelled in the fault tree. This provides a numerical significance of all the fault tree elements and allows them to be prioritised. The F-VIM is calculated by summing all the causes (MCSs) of the TE involving the particular event. This measure has been applied to MCSs to determine the importance of individual MCS (Trbojevic and Carr, 2000; Flage et al., 2013). The measure can be quantified as follows:

$$I_i^{fv}(t) = \frac{Q_i\,(t)}{Q_s\,(t)} \tag{15}$$

where, $I_i^{fv}(t)$ stands for the importance of minimal cut set (MC_i), Q_i (t) stands for the occurrence probability of MC_i and Q_s (t) stands for the occurrence probability of the TE due to all MCSs.

4. TEST CASE.

A numerical example is demonstrated in this section to show how the proposed modelling approach can be implemented to assess the various parameters that lead to a collision accident between an OSV and a platform under uncertainty. The phases of the proposed approach as presented in Section 3, and can be illustrated in a step-wise manner as follows.

4.1. *Preliminary System Analysis Phase.* This step involves a robust literature review and discussion with domain experts to identify hazards associated with an OSV collision with a platform, and a specific model for OSV/platform collision risk is constructed (Figure 2).

4.2. *Selection of Experts.* Expert elicitation is the synthesis of experts' opinions of a subject where there is uncertainty due to insufficient data because of physical constraints or lack of resources (John et al., 2016). Three experts whose experience spanned maritime and offshore systems design, operations and management with different length of service time, qualification, age and present job title were selected for this analysis and a set of questionnaires were prepared and implemented.

4.3. *Estimating Weights of Experts.* As presented in Section 3.3 and by using Equations (5) and (6) the weights of the experts can be calculated. The industrial positions, service times, and academic qualifications and age of the experts are extracted from Table 2. By using Equations (5) and (6), the weights of the experts are calculated and presented in Table 3.

Table 3. Weighting of Expert Judgements.

Expert No	Industrial Position	Service Time	Academic Qualification	Age	Weighting Factors	Experts' Weights
EXP 1	Operations manager	>30 years	Masters	>50	5 + 5 + 4 + 4 + 5 = 19	$\frac{19}{48} = 0{\cdot}40$
EXP 2	Chief engineer	10-19 years	Masters	40-49	3 + 3 + 4 + 4 = 14	$\frac{14}{48} = 0{\cdot}29$
EXP 3	Master mariner	20-29 years	Bachelors	40-49	4 + 4 + 3 + 4 = 15	$\frac{15}{48} = 0{\cdot}31$
					Total = 48	Total = 1

Table 4. Linguistic assessment of experts.

Basic events		Exp1	Exp2	Exp3
1	Failure of thrusters	Very High	High	High
2	Human errors	Medium	High	Very High
3	Extreme weather	High	High	High
4	Loss of support	Medium	Medium	High
5	Fatigue	Low	Medium	High
6	Dropped object	Medium	Low	Medium
7	Earthquake	Low	Low	Medium
8	Subsea collision	Low	Medium	Low
9	Connection leak	Low	Medium	Low
10	Corrosion	High	Medium	Medium
11	Loss of position	High	Medium	High

4.4. *Rating State.* In line with the modelling approach presented by John et al. (2016), the conversion scale of trapezoidal fuzzy membership function as illustrated in Figure 3 is used to analyse the experts' opinion presented in Table 4 on the occurrence probability of an OSV/platform accident during offshore operations, the figure contained both triangular and trapezoidal fuzzy numbers. All the triangular fuzzy numbers can be converted into the corresponding trapezoidal fuzzy numbers for the ease of computational analysis (Lavasani et al., 2012; Flage et al., 2013)). As previously mentioned, three experts are employed to rate the basic events for subsequent analysis, the background of the experts is briefly stated as follows:

- An offshore operations manager with a master's degree who has been involved with offshore operations for over 30 years.
- A master mariner with master's degree who has been involved with maritime and offshore systems design for over 20 years.
- A chief engineer with a master's degree who has been involved with maritime navigation for over 10 years.

In light of the above, the obtained trapezoidal fuzzy number assessed based on Figure 3 is illustrated in Table 5.

4.5. *Aggregating State.* It is important to aggregate the opinions of the experts to arrive at a consensus result. Therefore, the rating of experts on the list of each basic event is aggregated. As an example and by using Equations (7)-(11), the detail aggregation calculation for failure of thrusters is presented in Table 6.

Table 5. Conversion of linguistic terms to fuzzy numbers.

Linguistic terms	Trapezoidal fuzzy number
Very Low	(0·000, 0·000, 0·100, 0·200)
Low	(0·100, 0·250, 0·250, 0·400)
Medium	(0·300, 0·500, 0·500, 0·700)
High	(0·600, 0·750, 0·750, 0·900)
Very High	(0·800, 0·900, 1·000, 1·000)

Table 6. Demonstration of aggregation calculations for failure of thrusters.

EXP1	VH	0·8, 0·9, 1, 1
EXP2	H	0·6, 0·75, 0·75, 0·9
EXP3	H	0·6, 0·75, 0·75, 0·9
S(DM1&2) = 0·825		AA(DM1) = 0·825
S(DM1&3) = 0·825		AA(DM2) = 0·9125
S(DM2&3) = 1		AA(DM3) = 0·9125
RA(DM1) = 0·3113		CC(DM1) = 0·3328
RA(DM2) = 0·3443		CC(DM2) = 0·3635
RA(DM3) = 0·3443		CC(DM3) = 0·3035
Weight of DM1	0·40	
Weight of DM2	0·29	
Weight of DM3	0·31	
Aggregation Result	0·676, 0·807, 0·844, 0·938	

Table 7. Aggregation calculations results for all the basic events.

Basic events	Aggregated fuzzy trapezoidal numbers
Failure of thruster	(0·676, 0·807, 0·844, 0·938)
Human errors	(0·549, 0·703, 0·734, 0·856)
Extreme weather	(0·600, 0·750, 0·750, 0·900)
Loss of support	(0·392, 0·577, 0·577, 0·762)
Fatigue	(0·318, 0·483, 0·483, 0·649)
Dropped object	(0·242, 0·427, 0·427, 0·641)
Earthquake	(0·159, 0·323, 0·323, 0·488)
Subsea collision	(0·159, 0·323, 0·323, 0·488)
Connection leak	(0·159, 0·323, 0·323, 0·488)
Corrosion	(0·413, 0·593, 0·593, 0·775)
Loss of position	(0·512, 0·677, 0·677, 0·842)

Similar calculations were conducted on the other risk factors and their corresponding fuzzy estimates are presented in Table 7.

4.6. *Defuzzification State.* The aggregated trapezoidal fuzzy numbers presented in Table 8 are defuzzified using the centre of area defuzzification technique. As an example and by using Equation (12), the aggregated fuzzy numbers for failure of thrusters (0·676,

Table 8. Defuzzified results of basic events.

Basic events	Fault tree reference	Fuzzy possibilities
Failure of thruster	A	0·814
Human errors	B	0·708
Extreme weather	C	0·750
Loss of support	D	0·577
Fatigue	F	0·483
Dropped object	G	0·436
Earthquake	J	0·328
Subsea collision	K	0·323
Connection leak	H	0·323
Corrosion	I	0·593
Loss of position	E	0·677

0·807, 0·844, 0·938), is converted as follows; $\boldsymbol{a_1 = 0{\cdot}676}$, $\boldsymbol{a_2 = 0{\cdot}807}$, $\boldsymbol{a_3 = 0{\cdot}844}$ and $\boldsymbol{a_4 = 0{\cdot}983}$

$$X^* = \frac{1}{3}\frac{(0{\cdot}938 + 0{\cdot}844)^2 - 0{\cdot}938 \times 0{\cdot}844 - (0{\cdot}676 + 0{\cdot}807)^2 + (0{\cdot}676 \times 0{\cdot}807)}{(0{\cdot}938 + 0{\cdot}844 - 0{\cdot}676 - 0{\cdot}807)}$$

$$X^* = 0{\cdot}814$$

In a similar manner, the above procedure is repeated for all other basic events and the results are presented in Table 8.

4.7. *Converting Fuzzy Possibilities Scores to Fuzzy Failure Probabilities.* The crisp fuzzy failure possibilities scores presented in Table 8 are converted to fuzzy failure probabilities using Equations (13) and (14). As an example, the fuzzy possibility score for failure of thrusters (0·814) is performed as follows:

$$K = \left[\frac{1 - 0{\cdot}814}{0{\cdot}814}\right]^{(1/3)} \times 2{\cdot}301$$

$$K = 1{\cdot}41$$

$$F\,\mathrm{Pr} = \left\{\frac{1}{10^{1{\cdot}41}} = 0{\cdot}039\right.$$

The above calculation is repeated for all the other basic events and the results are presented in Table 9. The unit for basic events' failure probability is per year (/yr).

4.8. *Estimation of Failure Probability of TE.* To quantify the occurrence likelihood of the TE of the FT model, the occurrence likelihood for each basic event must be obtained and propagated upward to the TE using Boolean relationships. The Basic Events (BE) probabilities of the fault tree model (Table 8) can be propagated upward using the MCSs. In light of the above, the MCSs are estimated using the Boolean algebra simplification rules, and the occurrence likelihood of TE is obtained based on Equation (4) as 0·00410/year.

4.9. *Ranking of Minimal Cut Sets and Sensitivity Analysis.* An important objective of ranking parameters and performing sensitivity analysis tests in risk and reliability engineering is to identify those parameters or MCSs that are the most important so that they can be targeted for improvements. Table 10 presents the ranking of MCSs based on their calculated importance levels.

Table 9. Results of basic events failure probabilities.

Basic events	Fault tree reference	Result of basic failure probabilities (/yr)
Failure of thruster	A	0·0390
Human errors	B	0·0194
Loss of support	C	0·0190
Loss of position	D	0·0084
Fatigue	E	0·0044
Dropped object	F	0·0031
Earthquake	G	0·0012
Subsea collision	H	0·0012
Connection leak	I	0·0012
Corrosion	J	0·0016
Extreme weather	K	0·0093

Table 10. Ranking of Minimal Cut Sets.

Cut set	Importance of minimal cut sets
AB	$7{\cdot}57 \times 10^{-4}$
CDEF	$2{\cdot}18 \times 10^{-9}$
GH	$1{\cdot}44 \times 10^{-6}$
BI	$2{\cdot}32 \times 10^{-5}$
JK	$1{\cdot}49 \times 10^{-5}$

Whichever sensitivity analysis tests employed (Dimensional Consistency Tests (DCT), Boundary Adequacy Tests (BAT), Structure Verification Tests (SVT) (Forrester and Senge, 1980) and Sensitivity-Valued Approach (SVA) (Coupe and van der Gaag, 2002)) largely depend on the type of model developed to achieve a particular need. For the purpose of this paper and due to the fact that it has not been possible to find any proven benchmark results for its full validation, a possible method of validating the model can be achieved by using an incremental process, through conducting more industrial case studies. The developed model can then be refined and applied in real industrial applications. In light of the above, a partial validation may be the most realistic way to validate the proposed model using sensitivity analysis. Therefore, when conducting sensitivity studies, input parameters such as a component failure probability is changed, and the corresponding change in the TE probability is obtained. This analysis is performed for a certain amount using either different values for the same parameter or changing different parameters, e.g., changing different failure probabilities for this analysis. Hence sensitivity analysis is implemented to observe the effect on the output data (TE) given an increase in the input data (basic event). Figure 4 depicts the changes in the final ranking of the basic events when their failure probabilities were changed by 10%, 20% and 30% respectively. This is to help identify the basic event with the highest effect on the occurrence probability of the TE.

Table 10 presents the ranking of MCSs based on their calculated importance levels as presented in Equation (15).

5. RESULTS AND DISCUSSION.

From the result of the analysis in Table 10, the ranking of the MCS indicated that failure of thrusters and human error (AB) has the highest

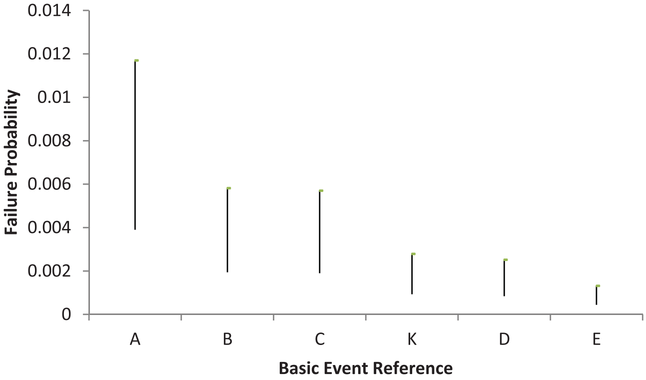

Figure 4. Ranking of Basic Events.

contribution of $7{\cdot}57 \times 10^{-4}$ to the occurrence probability of the TE. This implies that more attention needs to be focused on preventing AB from occurring to prevent or minimise the occurrence probability of the TE or OSV/platform collision. The MCS external weather event and human error (BI) has the second highest factor of $2{\cdot}33 \times 10^{-5}$, cut set (corrosion and connection leak) has the contributing factor of $1{\cdot}49 \times 10^{-5}$, cut set (earthquake and subsea collision) has the contributing factor of $1{\cdot}44 \times 10^{-6}$ and cut set (loss of support, loss of position, drop object and fatigue) with the contributing factor of $2{\cdot}18 \times 10^{-9}$. It is worth mentioning that to reduce or prevent the occurrence of the TE, the occurrence probabilities of all the basic events must be reduced and special attention must be paid to failure of thrusters which has the highest contributing factor to the occurrence of OSV/platform collision thereby leading to flexible riser collapse during offshore operations.

6. CONCLUSION.

This paper has presented a fuzzy-based modelling approach to evaluate the risks of OSV collision with platforms during offshore operations in a simple and straight-forward manner. The methodology combines FST and FTA to overcome the inadequacy of traditional FTA. It is designed to assist maritime and offshore personnel in evaluating the probability of supply vessel collision with offshore platforms. FST allows experts to express their opinions on the failure probability of the BEs enabling the treatment of uncertainty. The approach can be applied to situations where diverse sets of data from different experts must be integrated and synthesized in the absence of exact data. The obtained value for risk of collision can then be incorporated into the platform QRA studies and safety case document to demonstrate that hazards have been identified and risks to personnel are at ALARP level. This information may be used during Hazard and Operability study (HAZOP) and Layers of Protection Analysis (LOPA) sessions for the platform. It is envisaged that the outcome will help analysts in proposing practical measures that will help in avoiding collision of vessels with installations during operations.

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