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Fuzzy event tree analysis for quantified risk assessment due to oil and gas leakage in offshore installations

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Abstract. Accidental oil and gas leak is a critical concern for the offshore industry because it can lead to severe consequences and as a result, it is imperative to evaluate the probabilities of occurrence of the consequences of the leakage in order to assess the risk. Event Tree Analysis (ETA) is a technique to identify the consequences that can result from the occurrence of a hazardous event. The probability of occurrence of the consequences is evaluated by the ETA, based on the failure probabilities of the sequential events. Conventional ETA deals with events with crisp failure probabilities. In offshore applications, it is often difficult to arrive at a single probability measure due to lack of data or imprecision in data. In such a scenario, fuzzy set theory can be applied to handle imprecision and data uncertainty. This paper presents fuzzy ETA (FETA) methodology to compute the probability of the outcomes initiated due to oil/gas leak in an actual offshore-onshore installation. Post FETA, sensitivity analysis by Fuzzy Weighted Index (FWI) method is performed to find the event that has the maximum contribution to the severe sequences. It is found that events of 'ignition', spreading of fire to 'equipment' and 'other areas' are the highest contributors to the severe consequences, followed by failure of 'leak detection' and 'fire detection' and 'fire water not being effective'. It is also found that the frequency of severe consequences that are catastrophic in nature obtained by ETA is one order less than that obtained by FETA, thereby implying that in ETA, the uncertainty does not propagate through the event tree. The ranking of severe sequences based on their probability, however, are identical in both ETA and FETA.

Keywords: oil and gas leakage; event tree analysis; fuzzy weighted index

1. Introduction

Oil and gas leakage in offshore installations may have catastrophic consequences. The sources of such leakages could be many, e.g., it may be due to large inventory of oil and gas at high pressure in risers and pipelines, failure of valves, material failure at bends etc. Oil and gas leaks could occur in pipelines, risers or in the process area of the installation that may lead to fire or explosion. Event Tree Analysis (ETA) is a Quantitative Risk Assessment (QRA) technique that identifies all possible consequences that a system may suffer that have a probability of occurrence for a given initiating event (Ericson 2005, Vinnem 2014). ETA procedure is inductive and it seeks to incorporate all possible important outcomes that may occur from an initiating event, considering the success or failure of the events that are linked to the initiating event. The failure probability of

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the initiating (or top) event is utilized to compute the probability of occurrence of the outcomes. The branch points in the tree structure of ETA represent the success (or yes) and failure (or no) of the system that respond to the initiating event. Typically, an event tree analysis begins with the identification of an accidental (initial) event that gives rise to a series of unwanted consequences. This is followed by the identification of the barriers that exist to deal with the accidental event. This two steps are sufficient to construct the event tree.

In conventional ETA, the top (or initiating) event has a crisp value of probability of occurrence (Keneragui 1991, Ferdous *et al.* 2009, Lees 2005). In an offshore platform it is often difficult to arrive at the precise probability value for an event due to insufficient data or ‘vague’ characteristic of the events (Hu *et al.* 2012). In the absence of reliable data, probabilities are treated as random variables with known probability distributions. The difficulty with this approach is that probability distributions require the availability of data for modelling the event. The advantage of fuzzy approach is that it provides a way to determine the failure probability values when very little quantitative information is available (Misra and Weber 1990, Onisawa 1990, Suresh *et al.* 1996). In this approach, the probabilities are treated as fuzzy numbers. An additional benefit of using the fuzzy set theory is that it helps in accounting for the imprecision and uncertainty of the available data by providing a range of values. Fuzzy set theory has been applied to fault tree analysis for estimating the failure probability of oil and gas transmission (Yuhua and Datao 2005) and in subsea production system (Lavasani *et al.* 2011). Silvianita *et al.* (2013) have employed conventional ETA for anchor failure of floating structures to evaluate the frequency of failure for the consequences.

Whereas ETA has been applied to risk scenarios of oil and gas industry, it is rare to find application of fuzzy event tree analysis to the problems of this industry. FETA has been applied to the problems of oil and gas pipelines (Shan *et al.* 2017, Wang *et al.* 2017). In Ramzali *et al.* (2015), the fuzzy approach to ETA to offshore drilling system consisted of extracting fuzzy probability measures of events and converting them to crisp values, but it did not actually used fuzzy probabilities to compute the consequences. Though application of ETA is well described for leakage scenarios in offshore installations (Vinnem 2014), there had been no attempt to use the fuzzy set theoretic approach to treat ETA in such leakage scenarios. This paper attempts this for the first time.

In this paper, fuzzy event tree analysis (FETA) is proposed as a method to study the consequences of a leakage scenario developed in the context of a particular offshore-onshore installation in the Indian west coast, for which the failure data are ill quantified. Fuzzy probability has been used to represent the event probabilities. The event tree that is developed deals with a scenario in which the initiating event is the oil/gas leakage occurring in the process area of the offshore installation that mainly consists of wellheads, manifolds and separators. The severe outcome events are identified that respond to the top event which is the leakage. The analysis is carried out by employing the technique of fuzzy weighted index (FWI). This analysis results in a ranking of consequences that helps in taking preventive measures in the design stage and in strengthening the factors that have major contribution to the severe consequences. The methodology of FETA for an offshore installation that is presented in this work may be applied to other offshore installations with initiating events such as failure of mooring lines, failure of anchors and failure of pipelines etc.

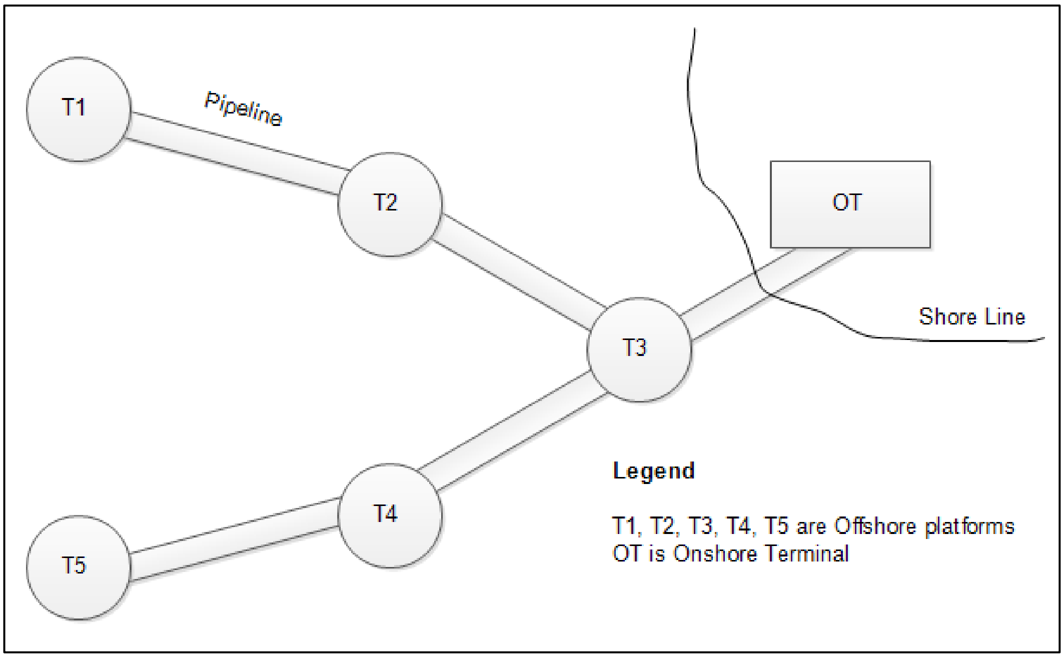


Fig. 1 Layout of the shallow water offshore-onshore gas field complex

2. Definition of the problem

The present work aims at developing a FETA methodology for modelling accident sequences in the process area of a specific shallow water offshore-onshore gas field complex located in the west coast of India. This complex is located in a shallow water block with water depth ranging between 10 to15 m. The field has five unmanned offshore platforms with similar physical layouts. The produced gas is conveyed to the onshore processing terminal by five pipelines of various sizes. Fig. 1 shows layout of the gas field (Ram Prasad 2010). All platforms are wellhead platforms, each having 6 well slots. Each platform has an approximate plan dimension of 18 m×10 m. There are two primary decks, namely, the cellular deck at elevation of 15 m and the main deck at elevation 20 m above the Mean Sea Level (MSL). Also, there are two more auxiliary decks with the sump deck at elevation 11 m and the helideck at elevation 25 m.

The cellular deck contains the pig launcher and receiver, the production manifold and wellhead panel. The main deck houses the test separator, instrument gas drum, vent knockout drum, chemical drum storage and injector pumps, vent boom, wellhead water filter and work bench. A sump deck is provided for the closed drain sump and closed drain transfer pump. A fresh water storage tank is located beneath the helideck.

The initiating event of a gas leakage that may occur in the process area of the offshore installation should be followed by the event of detection. This area mainly consists of wellheads, manifolds and separators. If the leak is detected, the operator interferes and performs the necessary action to curb it depending on the location of the leak. If the ‘operator interference is not successful’ (denoted OINS) or there is a detection failure, the event of ignition may occur. In the event of a failure in detection of oil and gas leakage followed by ignition, the fire detection failure would directly lead to the events of the fire spreading to equipment and other areas. If the fire is detected, the operator would interfere. If this operator interference is not successful, it would lead to emergency shut-down (ESD). The fire water which is sprayed after detection may or may not be sufficient leading to the spreading of the fire. Based on this understanding of the how the events may occur, an event tree is constructed as shown in Fig. 2.

In this figure, the events are denoted X_i (i = 1 to 10) and the outcomes, i.e., the sequences that result from the chain of events are denoted S_i (i = 1 to 25). The event tree is a double negated one, i.e., "Yes" (or success) represents the occurrence of a failure. The description of the events (Event 1 is X_1, etc.) are recorded in Table 1.

The more severe consequences of this event tree are S_1, S_4, S_7, S_{11}, S_{16} and S_{19}, as fire spreads to other areas making it catastrophic in these sequences. The primary task is to compute the probability of S_i through FETA. Further, it is necessary to identify those events which have high contribution to the severe sequences. This is performed using the FWI technique.

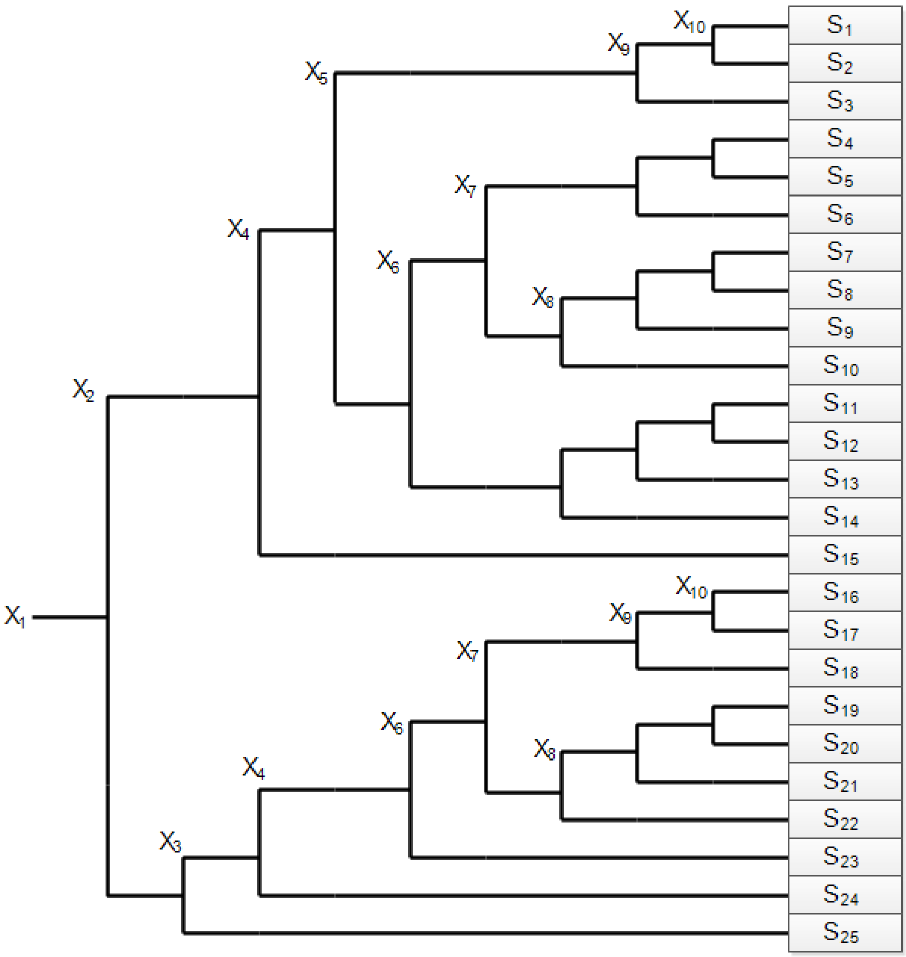


Fig. 2 Event tree for gas leak

Table 1 Events and their description

Event	Description	Comment
X_1	*Oil or gas leak*	Oil or gas leak in offshore terminal occurs due to sudden rupture of a pipeline/ riser, or in wellheads and manifolds of offshore platforms.
X_2	*Detection failure*	The event of gas leak has to be detected.
X_3	*Operator intervention not successful* (OINS)	If the leak is detected, then the operator would intervene to curb the leak. The operator would not be successful if the leak could not be stopped.
X_4	*Ignition*	There is a possibility of ignition from the leak that has occurred. The fires are generally due to oil pool fires or jet fires from gas leaks.
X_5	*Fire detection failure*	The failure of the detection of fire resulting from leak leads to this event.
X_6	*Operator intervention not successful*(OINS)	The controlling of fire by the operator could happen only if there is a detection of fire or oil/gas leak that has occurred.
X_7	*Emergency shutdown* (ESD) *failure*	If the operator intervention is not successful even after the detection of the fire, this would lead to the initiation of ESD.
X_8	*Fire water not effective*	This event indicates when the fire water used for containing the fire is not effective.
X_9	*Fire spreading to equipment*	The fire resulting from the leak may spread to equipment.
X_{10}	*Fire spreading to other areas*	The fire may further spread to other areas if there is oil spillage on other areas and there is a gas leak from other areas as well.

3. Fuzzy event tree analysis

3.1 Fuzzy probability

Fuzzy event tree analysis (FETA) helps in evaluating the probability of various outcomes in the event tree by considering the uncertainty of the events by propagating these uncertainties by fuzzification of the probabilities of the events, so that the probabilities of the outcomes are also fuzzy in nature. These fuzzy probabilities are then defuzzified to obtain the crisp values of the probabilities of the outcomes.

An event X_i can lead to an event X_j either by ‘yes’ (or success) or by ‘no’ (or failure) route. The resulting probability is given by

$$\begin{aligned} X_i \xrightarrow{Yes} X_j &: P(X_i)P(X_j) \\ X_i \xrightarrow[No]{} X_j &: P(X_i)(1-P(X_j)) \end{aligned} \tag{1}$$

where $P(X_i)$ is the probability of occurrence of the event X_i. This relation can be used successively along any path of the event tree.

A fuzzy number or a fuzzy set is a set of elements that have varying degree of membership in the set. But in a crisp set, an element is part of the set only when its membership is unity, else it is zero. A fuzzy number, on the other hand, can be mapped to a real numbered value in [0,1].The mapping of an element in its universe of discourse is given by the membership function. This function can be represented as triangular, trapezoidal or bell shaped curve (Chen 2000).

In fuzzy event tree analysis, the probability $P(X)$ of an event X, where $X \in [X_1, X_2, ..., X_{10}]$ in the event tree of Fig. 2, is considered a fuzzy number. In this paper, this number can either be a 'triangular fuzzy number' (TFN) or a 'trapezoidal fuzzy number' (TrFN). The membership function μ of $P(X)$ of a fuzzy number A, when $P(X)$ is a TFN, requires a triple point representation $\bar{P} = (P_1, P_2, P_3)$ and when it is a TrFN requires a quadruple point representation $\bar{P} = (P_1, P_2, P_3, P_4)$. The membership function is given by

$$\mu_A = \begin{cases} \dfrac{P - P_1}{P_2 - P_1} (P_1 \le P \le P_2) \\ \dfrac{P_3 - P}{P_3 - P_2} (P_2 \le P \le P_3) \\ 0 \quad \text{(otherwise)} \end{cases} \tag{2a}$$

for a TFN and

$$\mu_A = \begin{cases} \dfrac{P - P_1}{P_2 - P_1} (P_1 \le P \le P_2) \\ 1 \quad (P_2 \le P \le P_3) \\ \dfrac{P_4 - P}{P_4 - P_3} (P_3 \le P \le P_4) \\ 0 \quad \text{(otherwise)} \end{cases} \tag{2b}$$

for a TrFN (see Fig. 3).

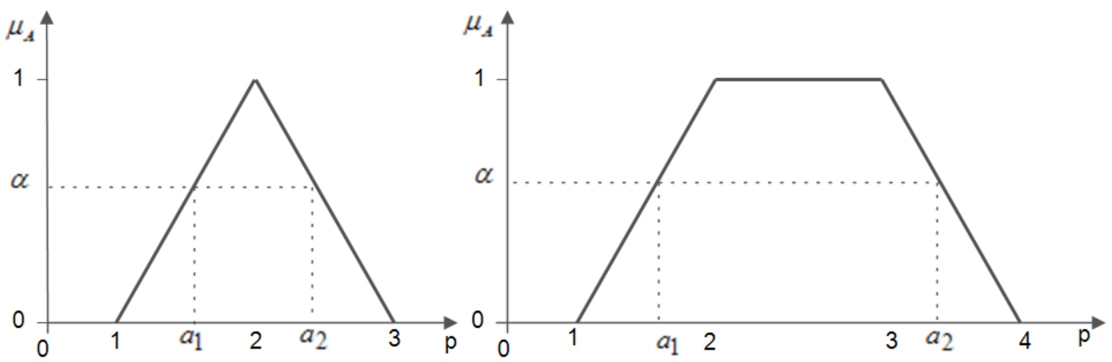


Fig. 3 Triangular and trapezoidal fuzzy numbers showing α cut

Table 2 Most possible failure probability and error factors of hardware failure events (From OGP Risk Assessment Data Directory, 2010 a, b)

Event	$P(X)$	Error factors	
		e_L	e_U
X_1	8.00E-02	10	3
X_4	1.50E-02	5	2

An event X can be one for which the probability of failure has been quantified through the detailed study of event occurrences, or it can be one for which the probability of failure has not been quantified due to unavailability of data and/or dependencies on the plant layout etc. Fuzzy set theory has been applied for both types of events.

3.2 Fuzzification of events

The statistics related to the oil and gas leaks have been used from the risk assessment data directories of International Association of the Oil and Gas Producers (IOGP). The two events, for which the probability has been modelled by IOGP are eventsX_1(oil or gas leak) and X_4 (ignition) (OGP 2010). The oil/gas release categories are dependent upon the release rates i.e., small releases (0-1 kg/s), medium releases (1-10 kg/s), large releases (>10 kg/s). The ignition probabilities are dependent upon the release rate. The values corresponding to a medium release event have been considered in the present problem. There is a need to account for the uncertainty in this data. For example, the uncertainty in the oil and gas release frequency may arise due to under reporting of events, measurement errors or inappropriate fit for frequency distribution.

Some of the events in the event tree may have reliable (or crisp) values of failure probability and are not fuzzy. In order to adopt FETA, which uses fuzzy arithmetic operations, one needs to convert such crisp values to fuzzy values. In other words, fuzzification of the events for which the probability is already quantified needs to be done. This is done by introducing two error factors, one for lower bound and the other for upper bound, as was proposed by Singer (1990), so that a TFN can be obtained. If $P(X)$ is the crisp probability of the event X, the corresponding TFN (P_1, P_2, P_3) is given by

$$P_1 = P / e_L, P_2 = P, P_3 = e_U P \tag{3}$$

where e_L and e_U are the lower and upper bound error factors, respectively. In the event tree of Fig. 2, the events X_1 (oil or gas leak) and X_4 (ignition), which are hardware failure events, can be assigned crisp failure probability values (i.e., most possible values) and error factors as given in Table 2.

Fuzzy failure probabilities of the events for which data is insufficient are derived by the method of expert elicitation wherein the subjective data of experts (based upon human feelings and experience) are systematically converted into fuzzy failure probabilities (Onisawa 1998, Lin and Wang 1998). This concept of reasoning using linguistic expressions for computation was first introduced by Zadeh (1996). Linguistic expressions, namely, “Very Low” (VL), “Low” (L), “Fairly Low” (FL), “Medium” (M), “Fairly High” (FH), “High” (H) and “Very High” (VH) are used by the experts for the judgement of the events.The corresponding fuzzy values of these linguistic expressions are listed in Table 3.

Table 3 Linguistic expression and values for human error events

Linguistic expression	Linguistic values A
Very Low (VL)	(0, 0.1, 0.2)
Low (L)	(0.1, 0.2, 0.3)
Fairly Low (FL)	(0.2, 0.3, 0.4, 0.5)
Medium (M)	(0.4, 0.5, 0.6)
Fairly High (FH)	(0.5, 0.6, 0.7, 0.8)
High (H)	(0.7, 0.8, 0.9)
Very High (VH)	(0.8, 0.9, 1)

Table 4 Assessment of human error events by experts

Event	Expert			
	1	2	3	4
X_2	M	M	FH	FH
X_3	M	FH	FH	H
X_5	FL	M	M	FH
X_6	FH	H	H	VH
X_7	FH	FH	FH	M
X_8	M	M	M	M
X_9	H	VH	H	H
X_{10}	VH	VH	VH	H

The opinion of the experts are aggregated to obtain a single opinion for each event by linear aggregation method given by Clemen and Winkler (1999)

$$M_i = \sum_{j=1}^{N_e} A_{ij} w_j \quad (i = 1, 2, ..., N) \tag{4}$$

where N is the number of events, N_e is the number of experts, w_j is the weighting factor of the expert j, A_{ij} is the linguistic expression of a basic event i given by the expert j and M_i is aggregated (resultant) number for X_i. The expert judgements for each of the events are listed in Table 4. In this case, the experts have equal weighting factor (= 0.25, since there are 4 experts).

The aggregated value M of an event X is termed "fuzzy possibility (FP)". This possibility is converted into "fuzzy probability" by employing a transformation function that has been defined by Onisawa (1988, 1990, 1993). The conversion of the fuzzy possibility to fuzzy failure probability (FFP or $\bar{P}$) is given by

$$\bar{P} = \begin{cases} \dfrac{1}{10^k} & M \neq 0 \\ 0 & M = 0 \end{cases}$$

$$k = 2.301 \left(\frac{1-M}{M} \right)^{1/3} \tag{5}$$

Table 5 Fuzzy failure possibility and fuzzy failure probability of human error events

Event	Fuzzy Possibility M	Fuzzy Probability $\overline{P}$
X_2	(0.45, 0.55, 0.6, 0.7)	(3.466E-03, 7.045E-03, 9.770E-03, 1.841E-02)
X_3	(0.525, 0.625, 0.675, 0.775)	(5.950E-03, 1.146E-02, 1.572E-02, 2.995E-02)
X_5	(0.375, 0.475, 0.525, 0.625)	(1.870E-03, 4.178E-03, 5.950E-03, 1.146E-02)
X_6	(0.675, 0.775, 0.825, 0.9)	(1.572E-02, 2.995E-02, 4.243E-02, 7.831E-02)
X_7	(0.475, 0.575, 0.65, 0.75)	(4.178E-03, 8.309E-03, 1.343E-02, 2.538E-02)
X_8	(0.4, 0.5, 0.5, 0.6)	(2.323E-03, 5.000E-03, 5.000E-03, 9.770E-03)
X_9	(0.725, 0.825, 0.85, 0.925)	(2.160E-02, 4.243E-02, 5.121E-02, 1.009E-01)
X_{10}	(0.775, 0.875, 0.95, 0.975)	(2.995E-02, 6.268E-02, 1.373E-01, 2.096E-01)

Table 6 Fuzzy failure probability ($\overline{P}$) of events

Event	$\overline{P}$				Centroid of $\overline{P}$
	P_1	P_2	P_3	P_4	
X_1	8.000E-03	8.000E-02	8.000E-02	2.400E-01	1.093E-01
X_2	3.466E-03	7.045E-03	9.770E-03	1.841E-02	9.964E-03
X_3	5.950E-03	1.146E-02	1.572E-02	2.995E-02	1.628E-02
X_4	3.000E-03	1.500E-02	1.500E-02	3.000E-02	1.600E-02
X_5	1.870E-03	4.178E-03	5.950E-03	1.146E-02	6.048E-03
X_6	1.572E-02	2.995E-02	4.243E-02	7.831E-02	4.281E-02
X_7	4.178E-03	8.309E-03	1.343E-02	2.538E-02	1.322E-02
X_8	2.323E-03	5.000E-03	5.000E-03	9.770E-03	5.698E-03
X_9	2.160E-02	4.243E-02	5.121E-02	1.009E-01	5.596E-02
X_{10}	2.995E-02	6.268E-02	1.373E-01	2.096E-01	1.112E-01

In Eq. (5), the FFP (i.e., $\overline{P}$) is a TrFN. The values of the aggregated fuzzy possibility and the final fuzzy probability for all the events with unavailable data are given in Table 5. Table 6 summarizes the fuzzy failure probability for all events. In all calculations, TrFN model given by Eq. (2(b)) has been used.

The fuzzy arithmetic operations in event tree analysis are performed by employing α - cut method based on the extension principle (Zadeh1965, Lai *et al*. 1993). The α - cut of a fuzzy number A defined in a universe of X, is given as the $A_\alpha = \{x \in X : \mu_A(x) \geq \alpha\}$ where α is any real number in the interval [0, 1]. The α cut of the fuzzy number $\overline{A}$ is shown in Fig. 3 and is described by the values of a_1 and a_2. In other words $A_\alpha = [a_1 \quad a_2]$. Similarly, for a fuzzy number $\overline{B}$, $B_\alpha = [b_1 \quad b_2]$. The fuzzy arithmetic operations are given by the extension principle proposed by Zadeh (1965) and are given by

$$A_\alpha \oplus B_\alpha = [a_1 + b_1 \quad a_2 + b_2]; A_\alpha \ominus B_\alpha = [a_1 - b_2 \quad a_2 - b_1]; A_\alpha \otimes B_\alpha = [a_1 b_1 \quad a_2 b_2] \quad (6)$$

Table 7 Lower bound, upper bound and defuzzified values

Seq. No.	I_L	I_U	P_S	Seq. No.	I_L	I_U	P_S
S_1	2.134E-11	9.272E-09	4.647E-09	S_{14}	2.643E-06	5.651E-05	2.957E-05
S_2	3.235E-10	4.667E-08	2.350E-08	S_{15}	2.481E-04	2.355E-03	1.301E-03
S_3	9.494E-09	5.453E-07	2.774E-07	S_{16}	1.896E-12	2.322E-09	1.162E-09
S_4	1.164E-12	1.433E-09	7.168E-10	S_{17}	2.854E-11	1.159E-08	5.808E-09
S_5	1.751E-11	7.150E-09	3.584E-09	S_{18}	8.295E-10	1.331E-07	6.697E-08
S_6	5.085E-10	8.215E-08	4.133E-08	S_{19}	1.114E-12	8.850E-10	4.430E-10
S_7	6.840E-13	5.460E-10	2.733E-10	S_{20}	1.675E-11	4.415E-09	2.216E-09
S_8	1.028E-11	2.724E-09	1.367E-09	S_{21}	4.863E-10	5.067E-08	2.558E-08
S_9	2.982E-10	3.127E-08	1.578E-08	S_{22}	1.177E-07	6.191E-06	3.155E-06
S_{10}	7.211E-08	3.823E-06	1.947E-06	S_{23}	4.345E-06	9.178E-05	4.806E-05
S_{11}	2.421E-11	7.716E-09	3.870E-09	S_{24}	4.034E-04	3.800E-03	2.102E-03
S_{12}	3.670E-10	3.882E-08	1.960E-08	S_{25}	4.253E-02	1.579E-01	1.002E-01
S_{13}	1.076E-08	4.532E-07	2.320E-07	SEV	5.041E-11	2.217E-08	1.111E-08

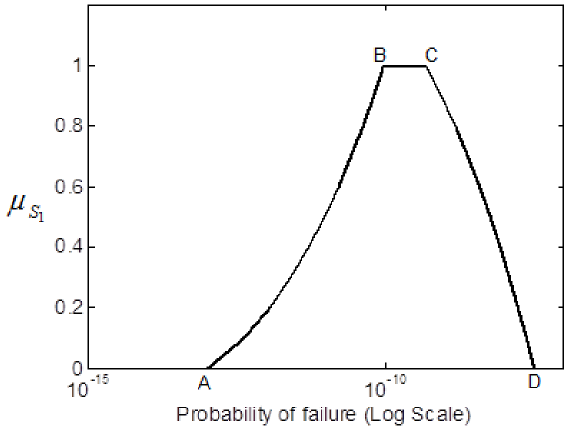
Fuzzy multiplication is employed across the events path according to Eq. (1) to determine the fuzzy probability of a sequence denoted by $\overline{P}_S$.

4. Defuzzification

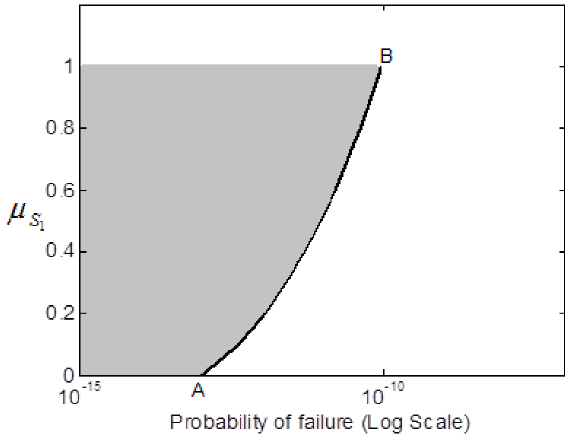
Defuzzification is the process of converting the fuzzy numbers to crisp values (Klir and Yuan 2001, Ross 2004, Sivanandam *et al.* 2007). Defuzzification method with total integral value as proposed by Liou and Wang (1992) is chosen as this matches α-cut operations and keeps the integrity of pertinent information. The defuzzification process to obtain a crisp probability value P_S for a sequence S with a fuzzy probability $\overline{P}_S$ is described by

$$P_S = \frac{1}{2}\left(I_U\left(\overline{P}_S\right) + I_L\left(\overline{P}_S\right)\right) \tag{7}$$

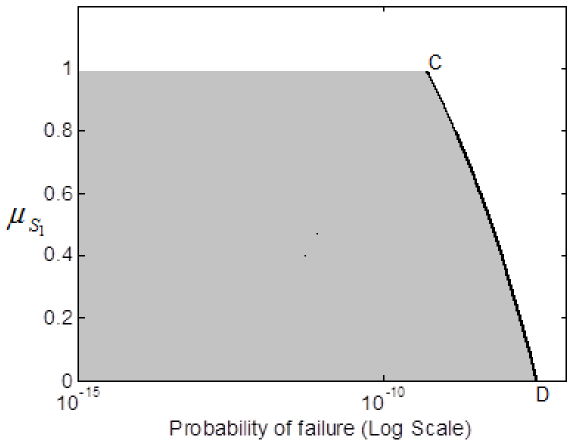
where $I_L\left(\overline{P}_S\right)$ and $I_U\left(\overline{P}_S\right)$ are the areas bounded by the lower and upper α-cuts respectively. As an illustration, Fig. 4(a) represents the fuzzy probability of the sequence S_1 of Fig. 2 and the shaded regions in Figs. 4(b) and 4(c) indicate the area bounded by lower and upper α-cuts respectively. Following this approach given by Eq. (7) and Fig. 4, the defuzzified crisp values for all sequences in Fig. 2 are shown in Table 7. The rank of the sequence is done in the descending order of its crisp value. The last row of the Table 7, is the summation of the α values of the severe sequences (denoted SEV) that consist of S_1 , S_4 , S_7 , S_{11} , S_{16} and S_{19}. These are sequences that pass through the event X_{10} (fire spreading to other areas) which is disastrous in nature.



(a) Fuzzy probability of sequence S_1



(b) Shaded region is I_L



(c) Shaded region is I_U

Fig. 4 Defuzzification process

5. Fuzzy Weighted Index

The Fuzzy Weighted Index (FWI) is an "importance index" proposed by Ferdous *et al.* (2009) and Misra and Weber (1990), which is usually generally applied in fuzzy fault tree analysis. This index gives the amount of contribution of each event makes to the failure of the entire system. In this paper, the concept of FWI has been applied to FETA. Here, the FWI is intended to find the contribution of each event in the severe consequence probability. The FWI of each event is computed by

$$FWI = \sum_{\alpha=0}^{1} \left| P(T)_\alpha - P(T_i)_\alpha \right| = \sum_{\alpha=0}^{1} \left[\left| P(T)_\alpha^L - P(T_i)_\alpha^L \right| + \left| P(T)_\alpha^U - P(T_i)_\alpha^U \right| \right] \tag{8}$$

where $P(T)_\alpha = [\, P(T)_\alpha^L \quad P(T)_\alpha^U \,]$ is the α-cut for the total fuzzy probability of the severe consequences and $P(T_i)_\alpha = [\, P(T_i)_\alpha^L \quad P(T_i)_\alpha^U \,]$ is the α-cut for the total fuzzy probability of the severe consequences when the probability of failure of event X_i is set to zero. Based on FWI values that are obtained, ranking of the events can be made to support the decision making system. In the ranking, the event that has the highest contribution is ranked 1. The FWI and ranks for each event have been presented in Table 8. It should be noted FWI ranks essentially indicate the 'sensitivity' of the risk of failure of the overall system on the events.

6. Results and discussion

The event of oil or gas leak in an offshore installation is a major concern. It may lead to catastrophic consequences such as spreading of fire to the entire installation which may lead to loss of life and assets. This paper computes the probabilities of various possible outcomes for a typical offshore installation in the west coast of India adopting the methodology of FETA. Fuzzy approach is used to arrive at the event probabilities because one of the major drawbacks of the oil and gas production industry is the non-availability of data and 'vagueness' of the modeled data. Events have been classified based upon the availability of data and fuzzification has been done accordingly. The concept of error factor has been employed for the events for which probability data are available and the concept of expert judgement into fuzzy probability has been used for the events that do not have recorded industrial data. The proposed methodology helps in the integration of both types of events to compute the output sequences. The fuzzy probabilities of the output sequences have been defuzzified to compute the crisp probabilities. Catastrophic sequences have been categorized as those in which the 'fire spreads to other areas'. The probabilities for all the sequences have been computed both by FETA as well as conventional ETA and reported in Table 9.

The total frequency of occurrence for these severe consequences have been computed to be 1.11×10^{-8} per year (see Table 9). The events X_4, X_9, X_{10}, i.e., ignition, spreading of fire to equipment and other areas respectively are the highest contributors for the severe consequences. The other major contributing events are X_2, X_5, X_8, i.e., failure of leak detection, failure of fire detection and fire water not being effective. Although, it is evident that the prevention of ignition and spreading of fire are the obvious events to be handled, the FWI indicates that it is critical that efficient fire detection and leak detection mechanisms be built such that the operator can react

Table 9 Probabilities of the outcome events by FETA and conventional ETA with ranks

Seq. No.	Probability of outcome by FETA	Rank	Probability of outcome by ETA	Rank
S_1	4.647E-09	17	6.558E-10	17
S_2	2.350E-08	13	5.242E-09	13
S_3	2.774E-07	8	9.949E-08	8
S_4	7.168E-10	23	6.100E-11	23
S_5	3.584E-09	19	4.875E-10	19
S_6	4.133E-08	11	9.254E-09	11
S_7	2.733E-10	25	2.594E-11	25
S_8	1.367E-09	21	2.074E-10	21
S_9	1.578E-08	15	3.936E-09	15
S_{10}	1.947E-06	7	7.275E-07	7
S_{11}	3.870E-09	18	5.878E-10	18
S_{12}	1.960E-08	14	4.698E-09	14
S_{13}	2.320E-07	9	8.918E-08	9
S_{14}	2.957E-05	5	1.648E-05	5
S_{15}	1.301E-03	3	1.072E-03	3
S_{16}	1.162E-09	22	9.927E-11	22
S_{17}	5.808E-09	16	7.934E-10	16
S_{18}	6.697E-08	10	1.506E-08	10
S_{19}	4.430E-10	24	4.222E-11	24
S_{20}	2.216E-09	20	3.375E-10	20
S_{21}	2.558E-08	12	6.405E-09	12
S_{22}	3.155E-06	6	1.184E-06	6
S_{23}	4.806E-05	4	2.698E-05	4
S_{24}	2.102E-03	2	1.733E-03	2
S_{25}	1.002E-01	1	1.064E-01	1
SEV	1.111E-08		1.472E-09	

quickly. It also signals the significance of sufficient fire water or different fire curbing techniques to prevent the fire from building up. The decision makers must ensure that these factors are taken care in the design or up-gradation of offshore installations to ensure a low risk environment. An optimum amount of redundancy can be introduced to ensure the same.

The frequency of severe consequences that are catastrophic in nature has been computed to be 1.472×10^{-9} per year by the conventional ETA method. This value is one order less than that obtained by FETA. This implies that, in FETA, the sequence probabilities are also fuzzy in nature and the uncertainty of all the events has been considered to compute the final crisp probability, whereas in conventional ETA the uncertainty does not propagate through the event tree.

Table 10 Probabilities of the severe consequences and their ranks (FETA vs. conventional ETA)

Sequence	Probability of outcome by FETA	Rank	Probability of outcome by ETA	Rank
S_1	4.647E-09	1	6.558E-10	1
S_4	7.168E-10	4	6.100E-11	4
S_7	2.733E-10	6	2.594E-11	6
S_{11}	3.870E-09	2	5.878E-10	2
S_{16}	1.162E-09	3	9.927E-11	3
S_{19}	4.430E-10	5	4.222E-11	5

Furthermore, Table 10 shows the ranks of the severe sequences (in descending order of their probabilities). It can be observed S_1 has the highest probability associated with it. Therefore, events in the path having highest probability for catastrophic consequences must be studied in detail to indemnify the effects of oil/gas leak.

Finally, the proposed FETA methodology for offshore installations can be improved by the usage of fuzzy probability distribution functions for the modelled data to arrive at probability values with more information.

7. Conclusions

A survey of the literature shows that it is rare to find application of FETA to the problems of oil and gas industry. Though application of ETA has been treated for leakage scenarios in offshore installations, there had been no attempt to use the fuzzy set theoretic approach for this class of problems. This paper attempts this for the first time by treating a case study of an actual offshore-onshore installation in the Indian west coast.

A comprehensive FETA methodology has been presented to compute the outcome probabilities due to oil and gas leakage. The ranking, alternatively the sensitivity, of the events that has the maximum contribution to the severe sequences has been obtained by FWI method. Since the uncertainty does not propagate through the event tree in ETA but does so in FETA, the frequency of severe consequences that are catastrophic in nature obtained by ETA is one order less than that obtained by FETA. The ranking of severe sequences, however, are identical in both ETA and FETA.

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