Risk Assessment of a NHT Heat Exchanger Using Bow Tie Analysis: An Intuitionistic Fuzzy Approach

Arjun P. Kumar and V. R. Renjith

1 Introduction

Risk assessment plays a vital role as far as an organisation aims to maintain the risk associated with its operation on a tolerable level. Many forms of risk assessment are there in practice today, of which fault tree analysis (FTA) is deductive technique including logic gates where all the potential causes to a top event (TE) are identified. If the probability of occurrence of these causes are known, obtaining the probability of the undesired event is attainable using Boolean logic. Event tree analysis (ETA) is an inductive technique where consequences arising out of/in the course of the undesired event can be identified. Once if the probability of occurrence of pivot events (PE) or failure probability of safety barriers is known, consequence probability can also be identified.

Heat exchangers are very important part as far as the refinery operations are concerned. It helps in decreasing the expenditure for heating purposes by utilising the heat given out by the product of different operation. Heat exchanger is sometimes given as a single one or as a series of the same. Although it requires less maintenance and attention, there is possibility that unexpected causes can create unwanted and undesired events in the operations. There are so many examples that can be pointed out relating to the catastrophic failure of heat exchanger and corresponding accidents. Some of those accidents that occurred due to the same are:

- The Esso Longford gas explosion was a catastrophic and major industrial accident that occurred at the Esso natural gas plant in Longford, Victoria, Australia, on

A. P. Kumar (✉)
Division of Safety and Fire Engineering, School of Engineering, CUSAT, 682022 Kochi, Kerala, India
e-mail: arjunpk@cusat.ac.in

V. R. Renjith
Faculty of Division of Safety and Fire Engineering, School of Engineering, CUSAT, 682022 Kochi, Kerala, India

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25 September 1998, killing two workers and injuring eight. Victoria State's gas supply severely affected for two weeks.

- The Tesoro Anacortes refinery disaster was an industrial accident at the Tesoro Anacortes refinery in Anacortes, Washington, on 2 April 2010. Seven workers sustained fatal burns in an explosion and fire that followed when a heat exchanger violently ruptured after a maintenance restart.
- The Williams Olefins Plant blast happened on 13 June 2013 at a petrochemical plant situated in Geismar, an unincorporated and to a great extent modern zone 20 miles southeast of Baton Rouge, Louisiana. Two labourers were killed, and 114 were harmed. A reserve heat exchanger had loaded up with hydrocarbon and was disengaged from its pressure relief; not long after the heat exchanger was heated up with boiling water, the hydrocarbon blazed to fume, cracked the warmth exchanger, and detonated.

Risk assessment of the vital parts of refinery operations can contribute to decrease in these undesirable events. The main problem in carrying out risk assessment is the unavailability of failure data. The proposed methodology makes use of expert opinions in linguistic terms for finding out failure probabilities and can be efficiently applied to the above-mentioned problem. Expert opinions collected are converted to crisp possibility and probability values using mathematical methods.

The methodology is applied in BT analysis where fault tree analysis and event tree analysis are carried out to identify the basic events and consequences related to the release prevention barrier failure. FTA method is a deductive technique where Boolean logic is used to illustrate the logical relations between undesired top event and its causes propagating through intermediate events. ETA method allows to obtain the occurrence probability of consequence by considering the failure probabilities of safety barriers or occurrence probability of pivot events related to initiating event. The basic event probabilities and pivot event probabilities are identified to obtain top event and consequence probabilities.

A naphtha hydrotreating unit is a part of refinery operations where the naphtha cut is introduced into the reactor after heating to remove the sulphur and nitrogen compounds. The processes associated with the same are always carried out at temperatures ranging between 205 and 260 °C. This heating is achieved by different means like preheating, reheater rotation of heated output feed through heat exchangers to transfer residual heat. Figure 1 shows a typical layout of NHT. The heat exchangers shown can either be a single one or be a series based on the heating needs. Since isolation of different components in the input feed is taking place at different temperature, different sections of equipment are present which in turn consist of heat exchangers operating at different temperatures which result in a complex system.

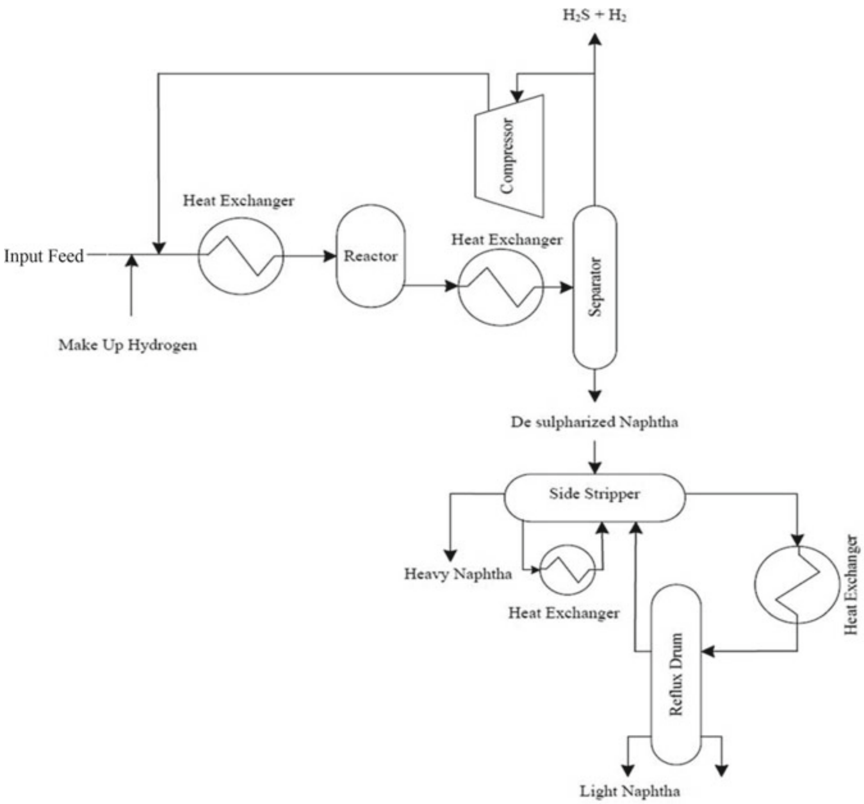

Fig. 1 Layout of a naphtha hydrotreater with heat exchangers

2 Materials and Methods

2.1 Basics of FTA

Conventional FTA

FTA makes use of logic gates to identify the possible paths and propagation of causes of a specific event to it undesired happening. Identification of the TE is the primary part in FTA, and afterwards, the path is drawn until the BEs are obtained. The AND and OR gates are the logic gates used in the analysis where AND gate represents the need of both the input events for happening of the output event where OR gate represents the need of only one of the events. The Boolean operations can be applied to estimate the probability of the undesired TE. Here, the probability values of the BE are either obtained from previous literatures.

FFTA

Zadeh [8] introduced the concept of fuzzy set theory and always been a prominent tool in risk assessment where sufficient data were not available. Fuzzy sets are defined on a universal set (X) characterised by a membership degree denoted by $\mu(x)$ in the interval [0, 1]. Here, $\mu(x)$ provides a measure of the degree of similarity of an element in X to the fuzzy subset. Fuzzy sets are defined for specific linguistic variables. The linguistic variables can be represented by different types of fuzzy numbers such as triangular, trapezoidal, or Gaussian shape membership function. In this paper, we make use of nonlinear triangular intutionistic fuzzy numbers to represent our linguistuc variables.

2.2 Basics of ETA

Conventional ETA

ETA is a forward-thinking logical method to identify the probabilities of outcomes by considering the failure of safety barriers (SB) or the pivot events (PE) that could occur as a result of the initiating event. The analysis progresses forwards considering the failure as well as success of the SB and PE considered. ETA is used as a tool to identify outcomes before occurring and setting up extra measures to prevent the possibility of occurrence.

FETA

FETA makes use of fuzzy set theory where proper data are not available in the case of failure probabilities. Expert elicitation with fuzzification, and further defuzzification enables to find the needed failure probabilities of SB's and occurrence probability of PEs.

2.3 Proposed Model

Concepts

Intuitionistic Fuzzy Method

Intuitionistic fuzzy sets were introduced by Atanassov [2] and are represented as follows:

Let A be an intuitionistic fuzzy set (IFS) in the universal set X defined as,

$$A = \{\langle x, \mu_A(x), v_A(x)\rangle | x \in X\}$$

Here, $\mu_A : X \to [0, 1]$ and $v_A : X \to [0, 1]$ are the membership and non-membership functions of an element $x \in A \subset X$ and for every $x \in X$ $0 \leq \mu_A(x) + v_A(x) \leq 1$

The method here involves the utilisation of fuzzification methods to convert linguistic terms to nonlinear triangular form of the fuzzy set, aggregation method to aggregate different fuzzy numbers, and final defuzzification methods to obtain the crisp possibility and probability scores.

Application of Methodology

The basic steps of the methodology applied by Kumar and Kaushik [4] can be summarised as follows:

- *Step 1:* FT and ET formulation
- *Step 2:* linguistic expert data collection
- *Step 3:* intuitionistic fuzzy failure probability (IFFP) evaluation
- *Step 4:* aggregation of opinions
- *Step 5:* defuzzification of IFFP to possibility and probability values
- *Step 6:* top event probability estimation.
- *Step 7:* pivot event probability estimation
- *Step 8:* consequence probability estimation

Step 1: FT and ET formulation

The FT was adopted from [1], and based on the same, the ET was constructed considering the PEs that could occur due to the TE considered. Fourteen possible consequences are identified with the help of ET (Fig. 2) (Tables 1, 2).

Step 2: Linguistic Expert Data collection

Qualitative data sets including seven linguistic terms, viz. VL, L, RL, M, RH, H, VH were introduced to the experts from different reas who have knowledge in the respective field, and opinions were collected. Both opinions about failure probability of BE and occurrence probability of PE are collected. Even though they may give dissimilar judgements, steps are taken in the following part to ensure weightage to experts and give importance to the more valuable opinion. Table 3 shows the details of the experts selected, and Table 4 is the opinions given by the experts w.r.t the BE and PE considered.

Step 3: Intuitionistic Fuzzy Failure Probability (IFFP) evaluation

The experts' opinions are converted to IFFP values with the help of previous literature. Huang et al. [3] and Liu et al. [5] developed the inductive approach, and it is used to represent the non-membership and membership values related to the failure probability of basic events. Initially, the extreme right and left sides' membership

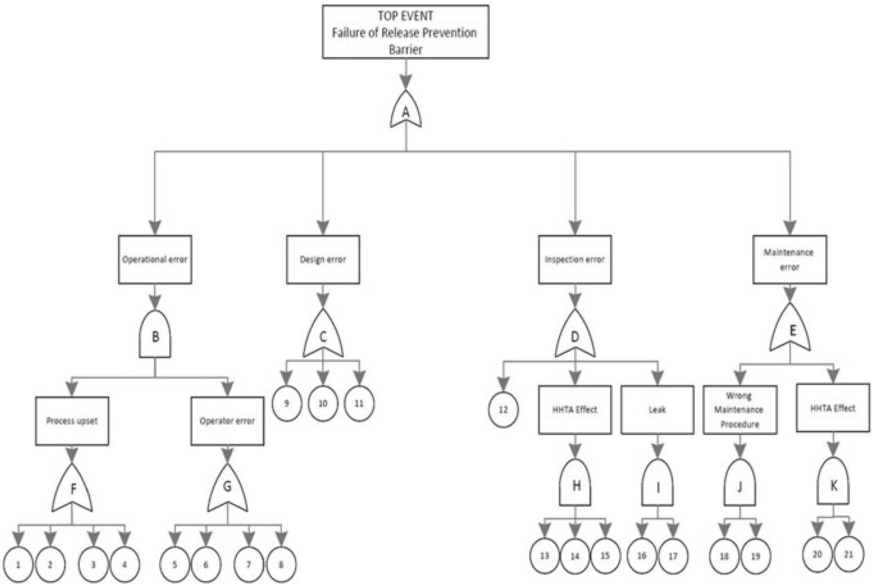

Fig. 2 Fault tree related to the top event

Table 1 Basic events adopted from [1]

Basic event	Basic event description
1	High temperature hydrogen attack (HTHA)
2	Difficulty with valve operation during start up
3	No report on leaks from heat exchanger during start up
4	Hydrogen induced cold cracking
5	Inexperience
6	No permit on job carrying
7	Failure of external supervision
8	Incorrect procedure
9	Poor construction material for NHT heat exchanger
10	High mechanical stress
11	Insufficient instrumentation to measure process conditions
12	Long delay in inspection schedule
13	Inadequate methods for detecting HTHA

(continued)

Table 1 (continued)

Basic event	Basic event description
14	Inadequate training of the inspectors to detect HTHA easily
15	Failure of HTHA inspection of heat exchanger
16	Failure of detection of leaks from heat exchanger flanges
17	Failure of minor release detection
18	Wrong maintenance procedure
19	Delay maintenance operations
20	HTHA degradation monitoring performed but failed to detect
21	HTHA degradation monitoring specified but not performed

Table 2 Identified consequences

Consequence	Consequence description	Outcome
1	Safe detection and rectification	Safe
2	Explosion and fire hazards causing minimal damage and casualties	Minimal damage and casualties
3	Explosion and fire hazards causing minimal damage with possible casualties	Minimal damage and possible casualties
4	Explosion and fire spread causing increased damages and possible casualties	Increased damage and possible casualties
5	Explosion and fire spread causing increased damages and casualties	Increased damage and casualties
6	Explosion and fire hazards causing moderate damages and possible casualties	Moderate damage and possible casualties
7	Explosion and fire hazards causing moderate damages and casualties	Moderate damage and casualties
8	VCE and fire hazards causing minimal damage and casualties	Minimal damage and casualties
9	VCE and fire hazards causing minimal damage with possible casualties	Minimal damage and possible casualties
10	VCE with fire spread causing increased damages and possible casualties	Increased damage and possible casualties
11	VCE and fire spread causing increased damages and casualties	Increased damage and casualties

(continued)

Table 2 (continued)

Consequence	Consequence description	Outcome
12	VCE and fire hazards causing moderate damages and possible casualties	Moderate damage and possible casualties
13	VCE and fire hazards causing moderate damages and casualties	Moderate damage and casualties
14	Formation of hazardous mixture with air	Hazardous atmosphere

Table 3 Details of selected experts

Expert	Professional position	Job experience (years)	Education
E1	Professor	15	Ph.D
E2	Manager	10	M.Tech
E3	Engineer	8	B.Tech
E4	Engineer	4	M.Tech
E5	operator	6	ITI

and non-membership functions of the TIFN are identified, and the two are selected to represent "very high" and "very low". Later to define the five other linguistic variables in between, the area in between the two IFN selected first is divided. Table 5 shows the IFFP values corresponding to the linguistic variables. These are the values which will be given to expert opinions and afterwards aggregated w.r.t the different opinions given related to BE and PE.

Step 4: Aggregation of opinions

In this step, the opinions given by the experts are then aggregated to obtain the aggregated IFFP. This happen in 7 steps and for understanding the calculations for a single BE is also given. BE 1 is selected, and the steps are applied to find out the aggregated IFFP of the event.

(a) *Calculation of Expectancy Evaluation*
The expectancy evaluation, $EE(A_i)$, for ith Expert (E_i) opinion's triangular IF number represented as $p_{ij} = \left(a_i, b_i, c_i; a_i', b_i, c_i'\right)$ can be found out using the formula,

$$EE(A_i) = \frac{\left(a_i + a_i{}'\right) + 4b_i + \left(c_i + c_i'\right)}{8}$$

Note that, TIFN numbers are taken as separate in the calculation and tabulation for the ease of calculation and should be considered as in the form represented above.

Table 6 shows the expectancy evaluations calculations corresponding to each of the experts utilising the formula.

Table 4 Opinions of selected experts

Opinions					
BE	*Expert 1*	*Expert 2*	*Expert 3*	*Expert 4*	*Expert 5*
1	RL	RL	L	L	RL
2	L	VL	L	L	VL
3	RL	VL	RL	L	L
4	VL	L	L	L	VL
5	VL	L	VL	L	VL
6	L	VL	VL	L	L
7	L	M	RL	M	M
8	L	VL	L	VL	L
9	VL	VL	L	L	L
10	L	VL	VL	L	L
11	VL	VL	VL	VL	L
12	VL	VL	VL	VL	L
13	M	RH	L	RL	L
14	RL	L	RL	L	VL
15	RL	L	M	L	L
16	VL	L	L	L	VL
17	VL	VL	VL	L	VL
18	VL	VL	VL	L	RL
19	L	VL	L	VL	L
20	RL	M	M	RL	L
21	L	RL	RL	RL	VL
PE	*Expert 1*	*Expert 2*	*Expert 3*	*Expert 4*	*Expert 5*
1	H	RH	RH	M	M
2	VH	VH	VH	H	H
3	H	VH	H	H	VH
4	M	RL	H	H	M
5	VH	H	VH	H	VH
6	M	M	RL	RL	RL

(b) *Calculation of Similarity degree and matrix*
The similarity between the opinions of the experts A_i and A_j selected is found out using the equation given, and the matrix is then formulated.

$$S(A_i, A_j) = \begin{cases} {EE(A_i)}/{EE(A_j)}; \; for\, EE(A_i) \le EE(A_j) \\ {EE(A_j)}/{EE(A_i)}; \; for\, EE(A_i) \ge EE(A_j) \end{cases}$$

Table 5 IFFP values of opinions

Opinion	IFFP values of opinions (general)						Probability
	a	b	c	a′	b′	c′	
VL	0	0.04	0.08	0	0.04	0.08	2.31E−07
L	0.07	0.13	0.19	0.06	0.13	0.2	4.61E−05
RL	0.17	0.27	0.37	0.15	0.27	0.39	6.23E−04
M	0.35	0.5	0.65	0.32	0.5	0.68	5.00E−03
RH	0.63	0.73	0.83	0.61	0.73	0.85	2.23E−02
H	0.81	0.87	0.93	0.79	0.87	0.95	6.01E−02
VH	0.92	0.96	1	0.92	0.96	1	1.59E−01

Table 6 Expectancy evaluations of BE 1

Basic Event 1 expectancy evaluation $EE(A_i)$					
Expert	1	2	3	4	5
Opinions	RL	RL	L	L	RL
Expert 1 (A_1) p_{ij}					
a	b	c	a′	b′	c′
0.17	0.27	0.37	0.15	0.27	0.39
$EE(A_1) = 0.27$					
Expert 2 (A_2) p_{ij}					
a	b	c	a′	b′	c′
0.17	0.27	0.37	0.15	0.27	0.39
$EE(A_2) = 0.27$					
Expert 3 (A_3) p_{ij}					
a	b	c	a′	b′	c′
0.07	0.13	0.19	0.06	0.13	0.2
$EE(A_3) = 0.13$					
Expert 4 (A_4) p_{ij}					
a	b	c	a′	b′	c′
0.07	0.13	0.19	0.06	0.13	0.2
$EE(A_4) = 0.13$					
Expert 5 (A_5) p_{ij}					
a	b	c	a′	b′	c′
0.17	0.27	0.37	0.15	0.27	0.39
$EE(A_5) = 0.27$					

For n experts, the similarity matrix can be formed as follows. Note that, for $i = j$, $S(A_i, A_j) = 1$

$$\begin{bmatrix} 1 & S_{(A_1,A_2)} & S_{(A_1,A_3)} & . & S_{(A_1,A_m)} \\ S_{(A_2,A_1)} & 1 & . & . & S_{(A_2,A_m)} \\ . & . & 1 & . & . \\ . & . & . & 1 & . \\ S_{(A_m,A_1)} & S_{(A_m,A_2)} & . & . & 1 \end{bmatrix}$$

Figure 3 shown below is the similarity degree matrix corresponding to BE 1 in the FTA. This is a 5 * 5 matrix since the number of experts selected is 5, and for all similar opinions, the term corresponding in the matrix will be equal to 1 (Fig. 4).

(c) *Calculation of Average Agreement Degree*

For each of the Experts E_i (for i = 1,2…, m) selected, the average agreement degree $AAD(E_i)$ can be found out using,

$$AAD(E_i) = \frac{1}{m-1}\sum_{j=1}^{m} S(A_i, A_j); i = (1, 2, \ldots, m), j \neq i$$

Table 7 shows the $AAD(E_i)$ w.r.t basic event selected, and $\sum AAD(E_i)$ is the sum of all degrees.

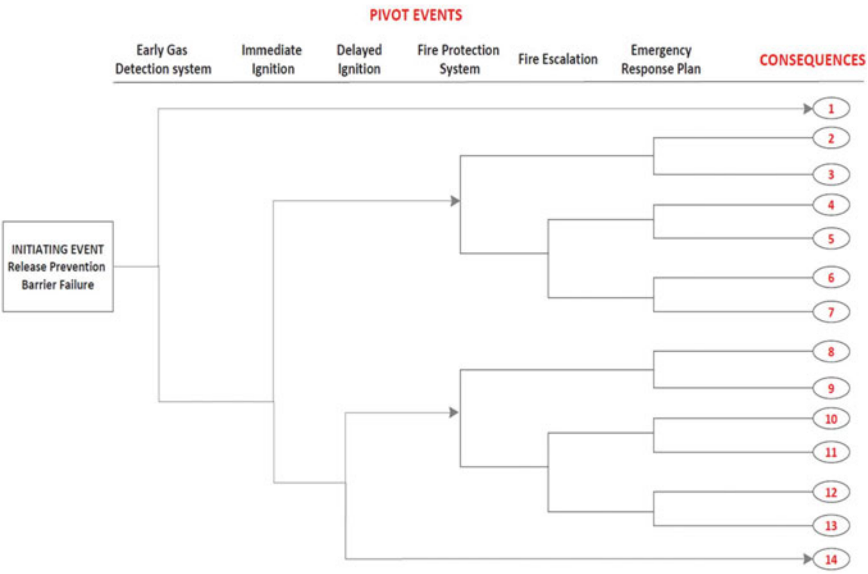

Fig. 3 Event tree related to the initiating event

	1	2	3	4	5
1	1	1	0.481481	0.481481	1
2	1	1	0.481481	0.481481	1
3	0.481481	0.481481	1	1	0.4814815
4	0.481481	0.481481	1	1	0.4814815
5	1	0.481481	0.481481	0.481481	1

Fig. 4 Similarity degree matrix for BE 1

Table 7 Average agreement degrees of BE 1

Average agreement degree $AAD(E_i)$ for BE1	
$AAD(E_1)$	0.740740741
$AAD(E_2)$	0.740740741
$AAD(E_3)$	0.611111111
$AAD(E_4)$	0.611111111
$AAD(E_5)$	0.611111111
$\Sigma\ AAD(E_i)$	3.314814815

(d) *Calculation of Relative Agreement Degree*
For each of the Experts E_i (for $i = 1, 2, \ldots, m$) selected, the relative agreement degree $RAD(E_i)$ can be found out using,

$$RAD(E_i) = \frac{AAD(E_i)}{\sum_{i=1}^{m} AAD(E_i)} i = (1, 2, \ldots, m)$$

Table 8 shows RAD calculations of BE 1 using the above formula which represents the relative agreement of experts in opinions w.r.t BE 1 (Tables 9, 10, 11 and 12).

(e) *Calculation of Weighing Factor*
Based on the profession, education, experience, the experts are given weighing scores. For each expert selected, the weighing score differs based on the mentioned parameters. This weightage of the score w.r.t the total weighing

Table 8 Relative agreement degrees of BE 1

Relative agreement degree $RAD\ (E_i)$ for BE 1	
$RAD\ (E_1)$	0.223463687
$RAD\ (E_2)$	0.223463687
$RAD\ (E_3)$	0.184357542
$RAD\ (E_4)$	0.184357542
$RAD\ (E_5)$	0.184357542

Table 9 Weighing factor criteria and scores for experts

Classification	Score
1. Professional position	
Professor, GM/DGM, Chief Engineer, Director	5
Assistant Professor, Manager, Factory Inspector	4
Engineer, Supervisors	3
Foreman, Technician, Graduate apprentice	2
Operator	1
2. Job experience (years)	
>=20	5
15 to 19	4
10 to 14	3
5 to 9	2
<5	1
3. Education	
Ph.D	6
M.Tech	5
MSc or B.Tech	4
Diploma or B.Sc.	3
ITI	2
Secondary school	1

Table 10 Weighing factors of selected experts

Expert	Position score	Experience score	Education score	Weighing score (WS)	Weighing factor (WF)
E1	5	4	6	15	0.3
E2	4	3	5	12	0.24
E3	3	2	4	9	0.18
E4	3	1	5	9	0.18
E5	1	2	2	5	0.1
	Total weighing score			50	

Table 11 Aggregated weights for BE 1

Aggregated weights (w) for BE_1	
w_1	0.261731844
w_2	0.231731844
w_3	0.182178771
w_4	0.182178771
w_5	0.142178771

Table 12 Aggregated IFFP for BE 1

Aggregated IFFP of BE 1 P_j ($\Sigma w_i * p_{ij}$)						
$w_i * p_{ij}$	a	b	c	a′	b′	c′
E1	0.044494	0.070668	0.096841	0.0392598	0.070668	0.102075
E2	0.039394	0.062568	0.085741	0.0347598	0.062568	0.090375
E3	0.012753	0.023683	0.034614	0.0109307	0.023683	0.036436
E4	0.012753	0.023683	0.034614	0.0109307	0.023683	0.036436
E5	0.02417	0.038388	0.052606	0.0213268	0.038388	0.05545
$\Sigma w_i * p_{ij}$	0.133564	0.21899	0.304416	0.1172078	0.21899	0.320772

score gives the weighing factor of the expert and is the indication of the importance of opinion given by the expert.

The weighing factor of the *i*th expert is as follows,

$$WF(E_i) = \frac{WS(E_i)}{\sum_{i=1}^{m} WS(E_i)}; i = (1, 2, \ldots, m)$$

(f) *Calculation of Aggregated Weights*

Aggregated weight w_i is the aggregation of the relative agreement degree $RAD(E_i)$ and weighing factor $WF(E_i)$ with and importance factor β where $(0 \leq \beta \leq 1)$. β shows the relative importance given to RAD and WF of experts.

Here, equal weightage is given to both RAD and WF so that β is assigned a value of 0.5, and the aggregated weight $w_i$is obtained as follows,

$$w_i = \beta.RAD(E_i) + (1 - \beta).WF(E_i); i = 1, 2, \ldots, m)$$

(g) *Calculation of Aggregated IFFP*

The calculation of aggregated IFFP is done by combining the opinions of the selected experts and can be done by using the equation given below,

$$P_j = \sum_{i=1}^{m} w_i \otimes p_{ij}; j = 1, 2, \ldots, n$$

Applying the method to the opinions given for other basic events, we get the IFFP for each as given in Table 13.

Step 5: Defuzzification of IFFP to possibility and probability values

The aggregated IFFP obtained thereby is converted to crisp possibility score and then to probability values by using centroid method of defuzzification proposed by Vargheese [7] and logarithmic function proposed by Onisawa and Nishiwaki [6], respectively. Therefore, for an IFFP represented as $\left(a_i, b_i, c_i; a_i', b_i, c_i'\right)$, the possibility score and probability are,

Table 13 Aggregated IFFP of basic event

Basic event	Intuitionistic fuzzy failure probability					
	a	b	c	a′	b′	c′
1	0.133564	0.21899	0.304416	0.117208	0.21899	0.320772
2	0.048065	0.101798	0.155531	0.041199	0.101798	0.162397
3	0.104432	0.179549	0.254665	0.091493	0.179549	0.267604
4	0.043174	0.095509	0.147845	0.037006	0.095509	0.154012
5	0.026213	0.073703	0.121192	0.022468	0.073703	0.124937
6	0.04443	0.097125	0.149819	0.038083	0.097125	0.156166
7	0.259442	0.381772	0.504101	0.235388	0.381772	0.528156
8	0.043787	0.096297	0.148808	0.037532	0.096297	0.155063
9	0.039587	0.090897	0.142208	0.033932	0.090897	0.147863
10	0.04443	0.097125	0.149819	0.038083	0.097125	0.156166
11	0.007942	0.050211	0.09248	0.006807	0.050211	0.093614
12	0.037983	0.09037	0.142757	0.033132	0.09037	0.147607
13	0.270858	0.369019	0.46718	0.251939	0.369019	0.486099
14	0.108077	0.184149	0.260221	0.094585	0.184149	0.273713
15	0.136525	0.21981	0.303094	0.121082	0.21981	0.318537
16	0.043174	0.095509	0.147845	0.037006	0.095509	0.154012
17	0.009279	0.05193	0.094581	0.007953	0.05193	0.095906
18	0.033783	0.08497	0.136157	0.029532	0.08497	0.140407
19	0.043787	0.096297	0.148808	0.037532	0.096297	0.155063
20	0.228582	0.343114	0.457646	0.20596	0.343114	0.480268
21	0.126585	0.210189	0.293794	0.11129	0.210189	0.309088

$$S = \frac{1}{3}\left[\frac{\left(c' - a'\right)\left(b - 2c' - 2a'\right) + (c - a)(a + b + c) + 3(c'^2 - a'^2)}{(c' - a' + c - a}\right]$$

$$P = \begin{cases} \dfrac{1}{10^{\left(\left[\frac{1-S}{S}\right]^{\frac{1}{3}} x2.301\right)}}; \ S \neq 0 \\ . \\ 0; \ S = 0 \end{cases}$$

$S =$ crisp probability score
$P =$ probability
Table 14 shows the defuzzified values of possibility scores and probability values of the 21 BE.

Table 14 Possibility and probability of basic events

Basic event	Intuitionistic fuzzy failure probability						Possibility(S)	Failure probability of basic events
	a	b	c	a′	b′	c′		
1	0.133564	0.21899	0.304416	0.117208	0.21899	0.320772	0.218989944	0.000305101
2	0.048065	0.101798	0.155531	0.041199	0.101798	0.162397	0.101797902	1.75891E−05
3	0.104432	0.179549	0.254665	0.091493	0.179549	0.267604	0.179548503	0.000151939
4	0.043174	0.095509	0.147845	0.037006	0.095509	0.154012	0.095509317	1.35453E−05
5	0.026213	0.073703	0.121192	0.022468	0.073703	0.124937	0.073702632	4.4687E−06
6	0.04443	0.097125	0.149819	0.038083	0.097125	0.156166	0.097124845	1.4515E−05
7	0.259442	0.381772	0.504101	0.235388	0.381772	0.528156	0.381771689	0.001985725
8	0.043787	0.096297	0.148808	0.037532	0.096297	0.155063	0.096297368	1.40125E−05
9	0.039587	0.090897	0.142208	0.033932	0.090897	0.147863	0.090897368	1.10258E−05
10	0.04443	0.097125	0.149819	0.038083	0.097125	0.156166	0.097124845	1.4515E−05
11	0.007942	0.050211	0.09248	0.006807	0.050211	0.093614	0.05021066	7.39707E−07
12	0.037983	0.09037	0.142757	0.033132	0.09037	0.147607	0.09036997	1.07603E−05
13	0.270858	0.369019	0.46718	0.251939	0.369019	0.486099	0.369018953	0.001772071
14	0.108077	0.184149	0.260221	0.094585	0.184149	0.273713	0.184149176	0.000166274
15	0.136525	0.21981	0.303094	0.121082	0.21981	0.318537	0.219809784	0.000309064
16	0.043174	0.095509	0.147845	0.037006	0.095509	0.154012	0.095509317	1.35453E−05
17	0.009279	0.05193	0.094581	0.007953	0.05193	0.095906	0.051929787	8.73243E−07
18	0.033783	0.08497	0.136157	0.029532	0.08497	0.140407	0.08496997	8.29313E−06
19	0.043787	0.096297	0.148808	0.037532	0.096297	0.155063	0.096297368	1.40125E−05
20	0.228582	0.343114	0.457646	0.20596	0.343114	0.480268	0.343113982	0.001389456
21	0.126585	0.210189	0.293794	0.11129	0.210189	0.309088	0.210189384	0.000264674

Step 6: Top event probability Estimation.

(a) *Cut Set Analysis*
Cut set analysis was done on FT to find out the most significant basic events or their combinations which when occurred will propagate and reach the TE. The probabilities of the cut sets were also calculated and shown in Table 15.

(b) *Calculation of Top Event Probability*
Making use of the simple Boolean algebra, the top event probability can be calculated. The basic operations on gates used here are as follows,

For an OR gate with two events as input, the probability of the output event P_{a+b} is,

$$P_{a+b} = P(a) + P(b) - P(a) * P(b)$$

Table 15 Cut sets of fault tree

Serial No	Cut set	Probability
1	BE 10	1.45E−05
2	BE 9	1.10E−05
3	BE 12	1.08E−05
4	BE 11	7.40E−07
5	BE 1, BE 7	6.06E−07
6	BE 20, BE 21	3.68E−07
7	BE 3, BE 7	3.02E−07
8	BE 2, BE 7	3.49E−08
9	BE 4, BE 7	2.69E−08
10	BE 1, BE 6	4.43E−09
11	BE 1, BE 8	4.28E−09
12	BE 3, BE 6	2.21E−09
13	BE 3, BE 8	2.13E−09
14	BE 1, BE 5	1.36E−09
15	BE 3, BE 5	6.79E−10
16	BE 2, BE 6	2.55E−10
17	BE 2, BE 8	2.46E−10
18	BE 4, BE 6	1.97E−10
19	BE 4, BE 8	1.90E−10
20	BE 18, BE 19	1.16E−10
21	BE 13, BE 14, BE 15	9.11E−11
22	BE 2, BE 5	7.86E−11
23	BE 4, BE 5	6.05E−11
24	BE 16, BE 17	1.18E−11

If the events are considered independent and $P(a) \cdot P(b)$ is very small, then the above equation can be approximated as

$$P_{a+b} = P(a) + P(b)$$

Therefore, for an n input gate, the equation becomes $P_{a+b+\cdots+n} = P(a) + P(b) + \cdots + P(n)$

For an AND gate with two independent events as input, the probability of the output event $P_{a.b}$ is,

$$P_{a*b} = P(a) * P(b)$$

Therefore, for an n input gate, the equation becomes $P_{a*b\ldots*n} = P(a) * P(b) * \cdots * P(n)$

Applying the above algebra on the FT using the obtained probability value BE, the probability of the top event P_T which is the *failure of release prevention barrier is estimated to be* ***2.65E−3***.

Step 7: Pivot Event Probability Estimation

The same method of aggregation is applied here for the opinions by experts, and final IFFP values are obtained. Afterwards, defuzzification procedures are done in order to get the possibility and probability values of PE.

Tables 16 and 17 show aggregated IFFP of PEs and list of PEs with estimated probability.

Step 8: Consequence Probability Estimation

Let

P_T = probability of occurrence of the TE.

P_1 = probability of occurrence/failure of PE 1.

Then, the success and failure probability of the first branch will be calculated as follows,

$$P(failure) = P_T * P_1$$

$$P(success) = P_T * (1 - P_1)$$

Similarly, successive failure and success probabilities of the upcoming branches are calculated until the ET reaches the undesired outcome/consequence. Table 18 shows the probability values of consequences obtained.

Table 16 Aggregated IFFP of pivot events

Pivot events	Intuitionistic fuzzy probability						Possibility score(S)	Crisp probability of pivot events
	a	b	c	a′	b′	c′		
1	0.5780511	0.6854301	0.7928091	0.5546432	0.6854301	0.816217	0.68543013	1.67928E−02
2	0.8827631	0.9295334	0.9763038	0.8759928	0.9295334	0.9830741	0.929533443	1.06208E−01
3	0.8502058	0.9028957	0.9555855	0.837516	0.9028957	0.9682754	0.902895674	8.04913E−02
4	0.4943334	0.5997112	0.705089	0.4701459	0.5997112	0.7292765	0.599711174	9.75180E−03
5	0.8752278	0.9233682	0.9715086	0.8670874	0.9233682	0.979649	0.923368212	9.91566E−02
6	0.2511691	0.373716	0.496263	0.2266597	0.373716	0.5207724	0.373716022	1.84873E−03

Table 17 List of pivot events with and probability

Pivot event	Pivot event description	Probability
1	Probability of failure of early gas detection system	1.67928E−02
2	Probability for immediate ignition	1.06208E−01
3	Probability for delayed ignition	8.04913E−02
4	Probability of failure of fire protection system	9.75180E−03
5	Probability of fire escalation	9.91566E−02
6	Probability of failure of emergency response	1.84873E−03

Table 18 Pivot events with estimated probability

Consequence	Consequence description	Outcome	Probability
1	Safe detection and rectification	Safe	2.60550E−02
2	Explosion and fire hazards causing minimal damage and casualties	Minimal damage and casualties	3.93140E−04
3	Explosion and fire hazards causing minimal damage with possible casualties	Minimal damage and possible casualties	7.28155E−07
4	Explosion and fire spread causing increased damages and possible casualties	Increased damage and possible casualties	3.48769E−06
5	Explosion and fire spread causing increased damages and casualties	Increased damage and casualties	6.45973E−09
6	Explosion and fire hazards causing moderate damages and possible casualties	Moderate damage and possible casualties	3.83892E−07
7	Explosion and fire hazards causing moderate damages and casualties	Moderate damage and casualties	7.17075E−09
8	VCE and fire hazards causing minimal damage and casualties	Minimal damage and casualties	4.29559E−05
9	VCE and fire hazards causing minimal damage with possible casualties	Minimal damage and possible casualties	7.05813E−10
10	VCE with fire spread causing increased damages and possible casualties	Increased damage and possible casualties	3.81077E−07
11	VCE and fire spread causing increased damages and casualties	Increased damage and casualties	7.05813E−10

(continued)

Table 18 (continued)

Consequence	Consequence description	Outcome	Probability
12	VCE and fire hazards causing moderate damages and possible casualties	Moderate damage and possible casualties	4.19455E−08
13	VCE and fire hazards causing moderate damages and casualties	Moderate damage and casualties	7.76894E−11
14	Formation of hazardous mixture with air	Hazardous atmosphere	3.80431E−06

3 Results and Discussions

Using the IFFP method, the failure probabilities of BEs, PEs, and consequences were identified. Tables 19, 20, and 21 show, respectively, the probability values of BEs,

Table 19 Basic events with probability in descending order

Basic event	Basic event description	Probability
7	Failure of external supervision	0.001985725
13	Inadequate methods for detecting HTHA	0.001772071
20	HTHA degradation monitoring performed but failed to detect	0.001389456
15	Failure of HTHA inspection of heat exchanger	0.000309064
1	High-temperature hydrogen attack (HTHA)	0.000305101
21	HTHA degradation monitoring specified but not performed	0.000264674
14	Inadequate training of the inspectors to detect HTHA easily	0.000166274
3	No report on leaks from heat exchanger during start up	0.000151939
2	Difficulty with valve operation during start up	1.75891E−05
6	No permit on job carrying	1.4515E−05
10	High mechanical stress	1.4515E−05
8	Incorrect procedure	1.40125E−05
19	Delay maintenance operations	1.40125E−05
4	Hydrogen-induced cold cracking	1.35453E−05
16	Failure of detection of leaks from heat exchanger flanges	1.35453E−05
9	Poor construction material for NHT heat exchanger	1.10258E−05
12	Long delay in inspection schedule	1.07603E−05
18	Wrong maintenance procedure	8.29313E−06
5	Inexperience	4.4687E−06
17	Failure of minor release detection	8.73243E−07
11	Insufficient instrumentation to measure process conditions	7.39707E−07

Table 20 Pivot events with probability in descending order

Pivot event	Pivot event description	Probability
2	Probability for immediate ignition	0.106208
5	Probability of fire escalation	0.099157
3	Probability for delayed ignition	0.080491
1	Probability of failure of early gas detection system	0.016793
4	Probability of failure of fire protection system	0.009752
6	Probability of failure of emergency response	0.001849

Table 21 Consequence with probability in descending order

Consequence	Consequence description	Outcome	Probability
1	Safe detection and rectification	Safe	0.02605499
2	Explosion and fire hazards causing minimal damage and casualties	Minimal damage and casualties	0.00039314
8	VCE and fire hazards causing minimal damage and casualties	Minimal damage and casualties	4.29559E−05
14	Formation of hazardous mixture with air	Hazardous atmosphere	3.80431E−06
4	Explosion and fire spread causing increased damages and possible casualties	Increased damage and possible casualties	3.48769E−06
3	Explosion and fire hazards causing minimal damage with possible casualties	Minimal damage and possible casualties	7.28155E−07
6	Explosion and fire hazards causing moderate damages and possible casualties	Moderate damage and possible casualties	3.83892E−07
10	VCE with fire spread causing increased damages and possible casualties	Increased damage and possible casualties	3.81077E−07
12	VCE and fire hazards causing moderate damages and possible casualties	Moderate damage and possible casualties	4.19455E−08
7	Explosion and fire hazards causing moderate damages and casualties	Moderate damage and casualties	7.17075E−09
5	Explosion and fire spread causing increased damages and casualties	Increased damage and casualties	6.45973E−09
9	VCE and fire hazards causing minimal damage with possible casualties	Minimal damage and possible casualties	7.05813E−10

(continued)

Table 21 (continued)

Consequence	Consequence description	Outcome	Probability
11	VCE and fire spread causing increased damages and casualties	Increased damage and casualties	7.05813E−10
13	VCE and fire hazards causing moderate damages and casualties	Moderate damage and casualties	7.76894E−11

PEs, and consequences in the descending order. As compared to other method, this method allows a clear ranking since all the probability values obtained will be have more significant figures.

4 Conclusions

This study shows that FTA and ETA along with the use of IF method yield a model which is simple as well as reliable for assessing the risk associated with events with unknown probability and uncertainties. Even though the risk associated with an instrument/process is less, it is always good to have the understanding about the same. For such a purpose, this model can be effectively and effortlessly applied. The method successfully identifies the probability associated with each of BE, PE, and consequences and reduces vagueness in the obtained values which helps in effective differentiation and ranking. However, the application and feasibility across different processes and equipment shall have to be found out by applying the method. Reducing the gap in the proposed approach by sensitivity analysis for importance factor, different importance analysis and its comparison, etc. is the modifications that have to be done in the approach.

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