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Approach to integrate fuzzy fault tree with Bayesian network

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Abstract

Fuzzy fault tree (FFT) can offer an efficient method of representing the fault causes and handling fuzzy information in the relationships among events. However, FFT cannot incorporate the evidence into the reasoning as Bayesian Network (BN). To overcome the disadvantage of FFT and BN, an approach of integrating FFT with BN is proposed in this paper. Firstly, the FFT technique of Takagi and Sugeno model that can handle uncertainties in the relationships among different events is introduced. Secondly, the translation rules of converting FFT into BN are presented. The integration algorithm is then demonstrated on an offshore fire case study.

Keywords: Fuzzy fault tree (FFT); Bayesian Network (BN); fuzzy analytical hierarchy process (FAHP); Fuzzy numbers

1. Introduction

In traditional fault tree analysis (FTA), the probabilities of basic events are treated as exact values, which could not reflect real situation of system because of ambiguity and imprecision of some basic events. In many circumstances, it is generally difficult to estimate the precise probabilities of basic events. Thus, it is often necessary to develop a new method to capture the imprecision of failure data. In this regard, it may be more appropriate to use fuzzy numbers instead of exact probability values [1]. The earliest work in fuzzy fault tree (FFT) treated possibilities of basic events as trapezoidal fuzzy numbers and applied the fuzzy extension principle to determine the occurrence probability of top event [2]. Singer also worked on this area by analyzing fuzzy reliability using standard approximations for the membership functions [3]. However, existing FFT methods cannot deal with uncertainties in relationships among events. Improvements have to be made to apply fuzzy gate to replace traditional gate.

Fault tree (FT) is entirely deterministic and no evidence can be given without re-evaluating the FT [4]. To overcome the shortcoming of FT, Bobbio et al. proposed the conversion algorithm of transforming FT into BN [5], which is a salutary lesson for the algorithm of transforming FFT into BN in this paper. For BN, the root nodes are ranked in terms of the conditional probability, which reflect the contribution to the probability of the eventual fault [6]. Updating the probability is possible when observation is performed on the system [7]. But BN is unable to determine accurately how the failures jointly cause the undesired fault, which is the advantage of FT [8]. To apply the above advantages of the two methods, FFT is integrated with BN in this paper, for which the probability calculation is more flexible and simpler. The description is organized as follows: In section 2, the method of FFT based on the Takagi and Sugeno model is introduced. Section 3 deals with how to transform FFT to BN. Section 4 carries out the possibility assessment of offshore fire.

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2. Fuzzy Fault Tree Analysis

The conventional gates of FT cannot function very well when there are uncertainties in the relationships among events. To handle this fuzzy information, a new gate based on the Takagi and Sugeno (T–S) model is presented. The failure possibility of the top event can be computed by the T–S model from the fuzzy possibilities of the basic events.

2.1. Takagi and Sugeno model

Takagi and Sugeno (T–S) model includes a set of IF-THEN fuzzy rules, which can be used to describe the relationships among events, leading to the construction of the T–S Gate. Consider the rule l of the T–S model [9]: Suppose the possibility magnitude of basic events $X_1, X_2, \ldots, X_n$ and upper event Y are denoted respectively by $(X_1^1, X_1^2, \ldots, X_1^{k1})$, $(X_2^1, X_2^2, \ldots, X_2^{k2})$, … , $(X_n^1, X_n^2, \ldots, X_n^{kn})$ and $Y^1, Y^2, \ldots, Y^{ky}$, which satisfy the following equations:

$$\begin{Bmatrix} 0 \le X_1^1 < X_1^2 < \cdots < X_1^{k1} \le 1 \\ 0 \le X_2^1 < X_2^2 < \cdots < X_2^{k2} \le 1 \\ \cdots \\ 0 \le X_n^1 < X_n^2 < \cdots < X_n^{kn} \le 1 \\ 0 \le Y^1 < Y^2 < \cdots < Y^{ky} \le 1 \end{Bmatrix}$$

Then the T–S gate can be represented by the following fuzzy rules,

$$\begin{cases} \text{Rule } l \ (l = 1, 2, \ldots, \text{m}): \\ \text{If } X_1 \text{ is } X_1^{i1}, \text{and } X_2 \text{ is } X_2^{i2}, \ldots, \text{and } X_n \text{ is } X_n^{in}, \text{then the possibility of } Y^1 \text{ is } P^l(Y^1), Y^2 \text{ is } P^l(Y^2), \ldots, Y^{ky} \text{ is } P^l(Y^{ky}). \end{cases}$$

"AND" "OR" gates in FTA can be implemented by T–S gate. "AND" gate can be represented by the following fuzzy rule:

$\{\text{If } X_1 \text{is } 1, \text{and } X_2 \text{ is } 1, \ldots, \text{and } X_n \text{ is } 1, \text{then the possibility of } Y^1 = 0 \text{ is } 0, Y^2 = 0 \text{ is } 0, \ldots, \text{the possibility of } Y^{ky} = 1 \text{ is } 1\}$

Whilst the "OR" gate can be represented by the following fuzzy rules:

$\{\text{Rule } l \ (\text{l} = 1, 2, \ldots, \text{m}): \text{If } X_l \text{ is } 1, \text{ then the possibility of } Y^1 = 0 \text{ is } 0, Y^2 = 0 \text{ is } 0, \ldots, \text{the possibility of } Y^{ky} = 1 \text{ is } 1\}$

First of all, to obtain fuzzy rules, the possibility magnitude of basic events should be defined according to historical data and experts' experience. After that, the fuzzy failure possibilities of top event can be estimated using fuzzy logic. Suppose the possibility of basic event is $X' = (X_1', X_2', \ldots, X_n')$, possibility of top event can be obtained by the T–S gate [10],

$$\begin{Bmatrix} P(Y^1) = \sum_{l=1}^{m} \beta_l^*(X')P^l(Y^1) \\ P(Y^2) = \sum_{l=1}^{m} \beta_l^*(X')P^l(Y^2) \\ \cdots \\ P(Y^k) = \sum_{l=1}^{m} \beta_l^*(X')P^l(Y^k) \end{Bmatrix} \tag{1}$$

$\beta_l^*(X') = \frac{\prod_{j=1}^{n} \mu(X_j')}{\sum_{l=1}^{m} \prod_{j=1}^{n} \mu(X_j')}$ and $\mu(X_j')$ is the membership of X_j' for the corresponding fuzzy set.

Suppose the fuzzy possibility of the basic events is $P(X_1^{i1})(i1 = 1,2, \ldots, k_1)$, $P(X_2^{i2})(i2 = 1,2, \ldots, k_2)$, …, $P(X_n^{in})(in = 1,2, \ldots, k_n)$, then the possibility of the rule l is : $P^l = P(X_1^{i1})\, P(X_2^{i2}) \ldots P(X_n^{in})$ $(l = 1,2 \ldots m)$.

The fuzzy possibility of the top event is then calculated by:

$$\begin{Bmatrix} P(Y^1) = \sum_{l=1}^{m} P^l \cdot P^l(Y^1) \\ P(Y^2) = \sum_{l=1}^{m} P^l \cdot P^l(Y^2) \\ \cdots \\ P(Y^k) = \sum_{l=1}^{m} P^l \cdot P^l(Y^k) \end{Bmatrix} \tag{2}$$

To obtain the fuzzy possibility of upper event at each state, the fuzzy possibility of upper event under each fuzzy rule is estimated using fuzzy AHP.

2.2. Calculate the possibility of upper events under each rule using fuzzy AHP

2.2.1. Rating state

Suppose an upper event Y, which has k states ($Y^1, Y^2, \ldots, Y^k$), is decided by n basic events $x_1, x_2, \ldots, x_n$. To elicit probabilities that Y is at some state (i.e.$P(Y^s)$), we should determine each $P^l(Y^s)$. In another words, we should estimate a probability weight $w = [w_1, w_2, \ldots, w_s, \ldots, w_k]$ under each rule, where w_s is the probability of $P^l(Y^s)$. Traditionally, w_s is specified directly by experts, using their knowledge and experiences. When the number of states is small, such a method may be feasible. With the increase of states of basic event, estimating probabilities directly to all states at one time may inevitably induce biases and inaccuracies.

An alternative way is giving fuzzy number to perform pair-wise comparisons between states for generating their probabilities. Since there are only two instead of n states considered at one time in a pair-wise comparison, it should be much easier to provide fuzzy linguistic variable than the direct estimation of probabilities. The fuzzy AHP method is able to solve uncertain 'fuzzy' problems. In the new approach, the probability of an upper event under some fuzzy rule can be determined by the following pair-wise comparison matrix [11]:

$$A = \begin{matrix} 1 & \tilde{c}_{12} & \cdots & \tilde{c}_{1k} \\ \tilde{c}_{21} & 1 & \cdots & \tilde{c}_{2k} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{c}_{k1} & \tilde{c}_{k2} & \cdots & 1 \end{matrix} \tag{3}$$

where A is the pair-wise comparison matrix. $\tilde{C}_{ij}$ is the comparison value of the likelihood of Y^i over that of Y^j. $\tilde{C}_{ij}$ is a triangular fuzzy number specified by asking the domain experts questions like "comparing states Y^i and Y^j, which one is more likely to occur and how much more?" Domain experts will answer the question using the following fuzzy linguistic scale. The linguistic evaluation scale, given in Table 1, can be used for triangular fuzzy numbers.

Table 1. Fuzzy scale in AHP

Linguistic scales	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just Equal	(1,1,1)	(1,1,1)
Equally probable	(1/2,1,3/2)	(2/3,1,2)
Weakly probable	(1,3/2,2)	(1/2,2/3,1)
Strongly more probable	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly more probable	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more probable	(5/2,3,7/2)	(2/7,1/3,2/5)

2.2.2. Calculating the probability of upper event under some rule

After the aggregation, the fuzzy pair-wise comparison matrix of upper event under some rule is defined. Then, the fuzzy weight matrix is calculated by Chang's Extent Analysis Method [12] as follows:

The value of fuzzy synthetic extent with respect to ith object is defined as:

$$S_i = \sum_{j=1}^{k} \tilde{C}_i^j \otimes [\sum_{i=1}^{k} \sum_{j=1}^{k} \tilde{C}_i^j]^{-1} \tag{4}$$

To obtain $\sum_{j=1}^{k} \tilde{C}_i^j$, perform the fuzzy addition operation of k extent analysis values for a particular matrix such that

$$\sum_{j=1}^{k} \tilde{C}_i^j = (\sum_{j=1}^{k} l_i^j, \sum_{j=1}^{k} m_i^j, \sum_{j=1}^{k} u_i^j) \tag{5}$$

To obtain $\left[\sum_{i=1}^{k} \sum_{j=1}^{k} C_i^j\right]^{-1}$, perform the fuzzy addition operation of $\sum_{j=1}^{k} \tilde{C}_i^j$ *(i=1,2,...k)* values such that

$$\sum_{i=1}^{k}\sum_{j=1}^{k}\tilde{C}_i^j = (\sum_{i=1}^{k} l_i, \sum_{i=1}^{k} m_i, \sum_{i=1}^{k} u_i) \quad (6)$$

and then compute the inverse of the vector :

$$\left[\sum_{i=1}^{k}\sum_{j=1}^{k}\tilde{C}_i^j\right]^{-1} = \left[\frac{1}{\sum_{i=1}^{k} u_i}, \frac{1}{\sum_{i=1}^{k} m_i}, \frac{1}{\sum_{i=1}^{k} l_i}\right] \quad (7)$$

The degree of possibility of $\tilde{C}_2 = (l_2, m_2, u_2) \geq \tilde{C}_1 = (l_1, m_1, u_1)$ is defined as:

$$V(\tilde{C}_2 \geq \tilde{C}_1) = sup_{y\geq x}[min\,(\mu_{\tilde{C}_2}(x), \mu_{\tilde{C}_1}(y)] \quad (8)$$

and can be equivalently expressed as follows:

$$V(\tilde{C}_2 \geq \tilde{C}_1) = hgt(\tilde{C}_1 \cap \tilde{C}_2) = \mu_{\tilde{C}_2}(d) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (9)$$

where d is the ordinate of the highest intersection point D between $\mu_{\tilde{C}_2}$ and $\mu_{\tilde{C}_1}$,To compare $\mu_{\tilde{C}_2}$ and $\mu_{\tilde{C}_1}$,

we need both the values of $V(\tilde{C}_2 \geq \tilde{C}_1)$ and $V(\tilde{C}_1 \geq \tilde{C}_2)$. The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy number $\tilde{C}_i$ (i=1, 2, …, k) can be defined by:

$$V(\tilde{C} \geq \tilde{C}_1, \tilde{C}_2, \ldots, \tilde{C}_k) = V[(\tilde{C} \geq \tilde{C}_1) and\ (\tilde{C} \geq \tilde{C}_2)\ and \ldots and\ (\tilde{C} \geq \tilde{C}_k)] = min\, V(\tilde{C} \geq \tilde{C}_{1i}),\ i=1,2,\ldots,k \quad (10)$$

Assume that $d'(A_i) = min\, V\,(S_i \geq S_n)$ n=1, 2,..., k; $n \neq i$. Then the weight vector is given by

$w' = (d'(A_1), d'(A_2), \ldots, d'(A_k))^T$ where $A_i (i = 1,2, \ldots, k)$ are k elements.

Via normalization, the normalized weight vectors are $w = (d(A_1), d(A_2), \ldots, d(A_k))^T$ (where w is a non-fuzzy number), which is the probability of upper event Y under some rule. After the probability of upper event Y under each rule is defined, we can substitute $P^l(Y^s)$ in the equation (2) to calculate the probability of upper event Y.

3. Converting Fuzzy Fault Tree to Bayesian Network

Generally, FT can be converted into BN, and inference technique of BN can be used to obtain classical parameters of FT [5]. Dynamic FT can also be mapped into an equivalent discrete-time Bayesian network [13]. Similarly, FFT can also be transformed into BN. To demonstrate how to integrate FFT with BN, the following assumptions are given:

(1) The failure possibilities of basic events are triple (high/medium/low correspond to 1/ 0.5/ 0 respectively).

(2) Relationships between basic events and top event are represented by fuzzy logical T–S gate.

FFT can be transformed into an equivalent BN as follows: (1) Each basic event in the FFT is converted into a corresponding child node in the BN. The child nodes are triple (high/medium/low) and let the failure magnitude of the corresponding state be 1, 0.5 and 0 respectively; (2)Each child node in BN is assigned the same prior probability as the possibility magnitude of basic event in FFT;(3)For each gate of the FFT, one relevant parent node is created in the BN; (4)Child nodes in the BN are connected to parent node as basic events are connected to the associated gates in the FFT;(5)Each parent node of BN is assigned to the same conditional probability as the relevant fuzzy T-S gate in FFT; the parent nodes in the BN are connected as the relevant gates are connected in the FFT. One example of converting OR, AND gate of FFT into equivalent nodes of BN is shown in Fig. 1.

4. Case Study

In this section, the integration algorithm mentioned above is demonstrated on an offshore fire case. Based on historical experiences, the fire and explosion hazard of separator, flash drum, drier and compressor are generally larger than other units' on offshore platform [14]. Taking flash drum unit as an example, the most credible fire scenario is vapor cloud explosion with fire: Gas release from flash drum and the released gas might produce flammable vapor clouds. If vapor cloud meets ignition source with delay, it will cause vapor cloud explosion. Firstly, the most credible fire scenario of flash drum unit is analyzed by FFT. Secondly, the FFT is converted to BN and the BN model is analyzed. Finally, the occurrence possibility of offshore fire scenario and the posterior probabilities of all basic events are predicted by BN inference.

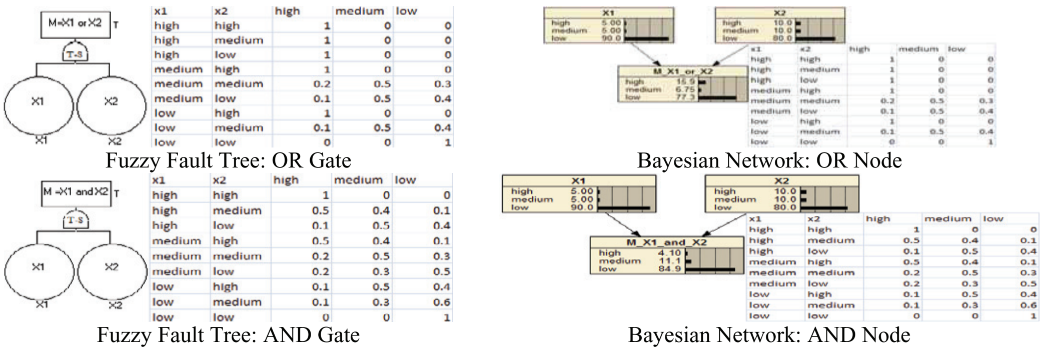

Fig.1. AND and OR gate of Fuzzy Fault Tree and Bayesian Network

4.1. Fuzzy fault tree analysis

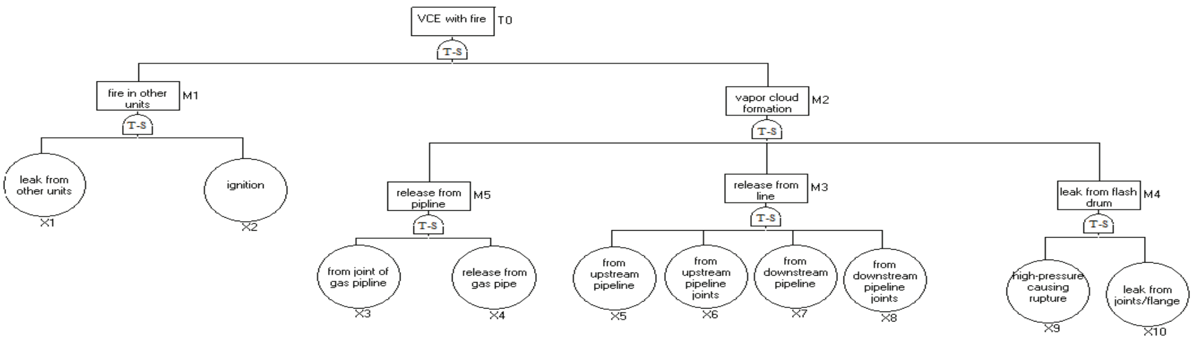

Fig.2. Fault tree of vapor cloud explosion with fire for flash drum

FFT is constructed to analyze causal effect of vapor cloud explosion in Fig.2. The possibilities of basic events are defined according to historical data, collected from Offshore Reliability Data Handbook [15]. Suppose the fuzzy possibilities of all basic events failing with a magnitude of 0.5 are the same as 1's. The possibilities of all basic events are shown in Table 2.

Table 2. Basic events of the fault tree for the most credible scenario of flash drum

	Basic event	possibilities of X=1	possibilities of X=0.5	possibilities of X=0
X_1	Release from other units	0.2	0.2	0.6
X_2	Ignition due to electric spark or external heat	0.35	0.35	0.3
X_3	Release from joint of gas pipeline	0.065	0.065	0.87
X_4	Release from gas pipeline	0.0045	0.0045	0.991
X_5	Release from upstream pipeline	0.003	0.003	0.994
X_6	Release from joints of upstream pipeline	0.045	0.045	0.91
X_7	Release from downstream pipeline	0.00003	0.00003	0.99994
X_8	Release from joints of downstream pipeline	0.045	0.045	0.91
X_9	High-pressure in vessel causing rupture of vessel	0.003	0.003	0.994
X_{10}	Release from joints or flange	0.0075	0.0075	0.985

Taking M_1 as an example, how the IF-THEN fuzzy rules can constitute a T-S gate is demonstrated as follows: Firstly, the experts express their judgments for the possibility of M_1 under each fuzzy rule. This can be carried out via linguistic terms according to Table1. Secondly, the possibility of M_1 under the fuzzy rule 1 is calculated using Chang's Extent Analysis Method. The calculation results of the possibility of M_1 under each fuzzy rule are shown in Table 3.

Table 3. Probability table of T-S GATE M_1

X_1	X_2	1	0.5	0
0	0	0	0.375	0.625
0	0.5	0	0.411	0.589
0	1	0	0.485	0.515
0.5	0	0	0.436	0.564
0.5	0.5	0.212	0.324	0.464
0.5	1	0.467	0.221	0.312
1	0	0	0.398	0.602
1	0.5	0.413	0.218	0.369
1	1	0.751	0.249	0

The fuzzy possibility of M1 can be obtained according to T–S model as follows:

$$P(M_1=1)=\sum_{l=1}^{27}P^l\cdot P^l(M_1=1)=\sum_{l=1}^{27}P^l(X_0)\cdot P^l(X_1)\cdot P^l(X_2)\cdot P^l(M_1=1)=0.12901;$$

$$P(M_1=0.5)=\sum_{l=1}^{27}P^l\cdot P^l(M_1=0.5)=\sum_{l=1}^{27}P^l(X_0)\cdot P^l(X_1)\cdot P^l(X_2)\cdot P^l(M_1=0.5)=0.37654;$$

$$P(M_1=0)=\sum_{l=1}^{27}P^l\cdot P^l(M_1=0)=\sum_{l=1}^{27}P^l(X_0)\cdot P^l(X_1)\cdot P^l(X_2)\cdot P^l(M_1=0)=0.49445.$$

The fuzzy possibilities of T–S gates are calculated using the same way. Their calculation results are shown in Table 4.

Table 4. Fuzzy possibility of each T–S gate

T–S gate	High(1)	Medium(0.5)	Low(0)
M_1	0.12901	0.37654	0.49445
M_2	0.06064	0.094216	0.845148
M_3	0.0389	0.046854	0.914247
M_4	0.004683	0.176941	0.818376
M_5	0.003127	0.142215	0.854658
T_0	0.0852	0.08473	0.83

The failure possibilities of vapor cloud explosion with fire for flash drum unit can be calculated as follow:

$$P(T_0=1)=\sum_{l=1}^{27}P^l\cdot P^l(T_0=1)=\sum_{l=1}^{27}P^l(M_1)\cdot P^l(M_2)\cdot P^l(M_4)\cdot P^l(T_0=1)=0.0852;$$

$$P(T_0=0.5)=\sum_{l=1}^{27}P^l\cdot P^l(T_0=0.5)=\sum_{l=1}^{27}P^l(M_1)\cdot P^l(M_2)\cdot P^l(M_4)\cdot P^l(T_0=0.5)=0.08473;$$

$$P(T_0=0)=\sum_{l=1}^{27}P^l\cdot P^l(T_0=0)=\sum_{l=1}^{27}P^l(M_1)\cdot P^l(M_2)\cdot P^l(M_4)\cdot P^l(T_0=0)=0.83$$

4.2. Converting fuzzy fault tree to Bayesian Network

According to the translation rules of converting FFT to BN, BN corresponding to above FFT is depicted in Fig.3. The possibilities of child node are the same as the possibilities of basic events, which are shown in Table 2. The CPTs of parent node are the same as the possibilities of fuzzy gate. Such as, the CPT of node "fire_in_other_units" is the same as the possibility of M_1 gate, which is shown in Table 3.

After all the CPTs are elicited, the probability analysis can be performed using Bayesian inference. From the Fig.3, it can be seen that the fuzzy possibility of top event is similar with the calculation results of FFT:

$$P(T_0=1)=0.0852;\ P(T_0=0.5)=0.0847;\ P(T_0=0)=0.83$$

The posterior probabilities of basic events given accident happened are estimated by BN, which is shown in Fig.4.

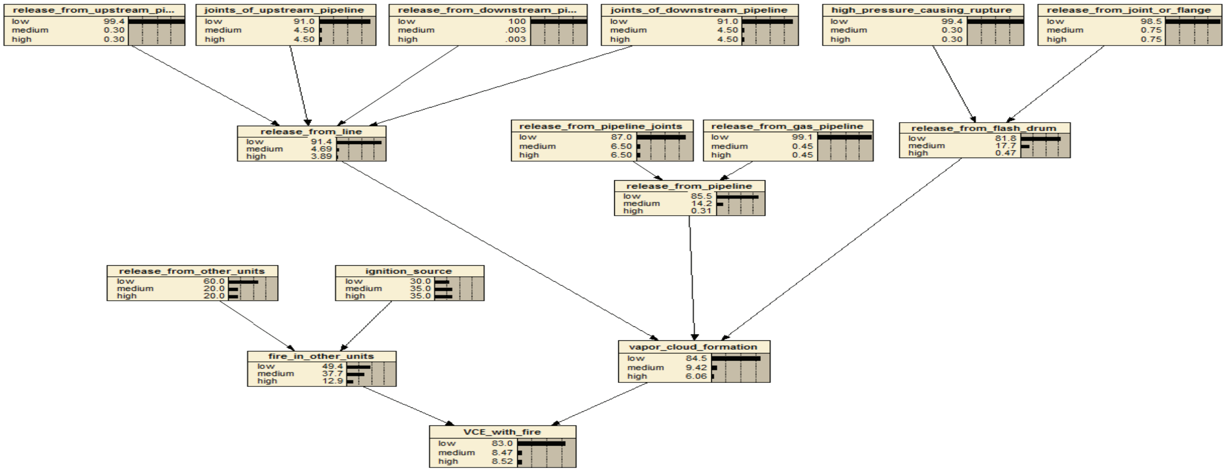

Fig.3. Bayesian network of vapor cloud explosion with fire for flash drum

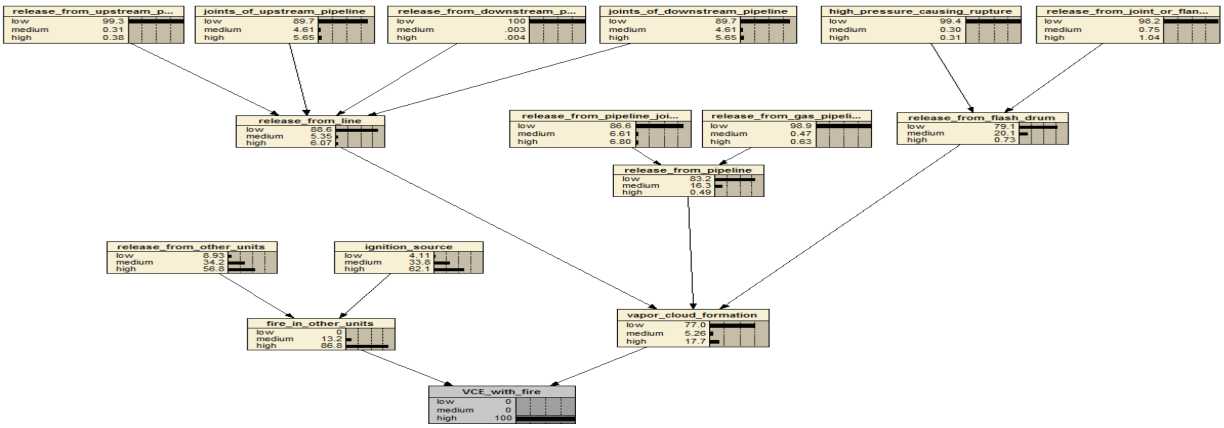

Fig.4. Posterior probabilities of basic events given the offshore fire happened

5. Conclusions

The fuzzy logic in FFT allows fuzzy information to be incorporated. Fuzzy gate can deal with uncertainties of the failure causes, due to insufficient knowledge of the relationships among basic events. Therefore FFT is more suitable for analyzing failure causes than traditional FT. BN is useful for assessing probabilistic relationships among basic events.

The case study shows that FFT can be directly converted into BN and BN can be used for predicting the marginal posterior probabilities of basic event, which is often used to identify the criticality of basic events. Controlling the occurrence possibility of these crucial events would considerably reduce the possibility of accidents. The model of combining FFT and BN is more flexible and useful than traditional FT model.

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