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Safety Assessment of Process Systems using Fuzzy Extended Bow Tie (FEBT) Model

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Risk analysis in process systems is very important to design effective strategies for preventing and mitigating potential major accidents. Although conventional techniques as Bow-tie (BT) have widely been used in risk assessment of process systems, they fall short in effectively modelling epistemic uncertainty which is prevailing in risk assessment of process systems. The present study is aimed at alleviating this shortcoming by incorporating fuzzy set theory into BT, developing a so-called fuzzy extended Bow tie (FEBT) model. FEBT, compared with previous fuzzy BT methods, uses the intuitionistic fuzzy numbers and thus provides a more accurate cause – consequence model of accident scenarios. A natural gas transmission network is used to demonstrate the application of FEBT.

1. Introduction

Chemical process plants are progressively being built and exploited on a large scale due to growing demands of chemical products. In order to meet this demand, process installations often operate continuously, which may negatively affect both their reliability and safety (Mkpat et al., 2018). Chemical process plants are more susceptible to catastrophic disasters due to handling various and huge amounts of hazardous materials which are stored or processed under severe conditions (Khan and Abbasi, 1998). Therefore, safety assessment is very crucial in order to measure risk and to design preventive and mitigative safety strategies in chemical process plants (Dormohammadi et al., 2014; Zarei et al., 2013). Different methods have been proposed to safety analysis and each of them have specific applications. Among various models Bow-tie (BT) diagram has played an impressive role in improving safety level of process systems during the last decades. BT is a robust model which provides a transparent and comprehensive cause–consequence modelling of accident scenarios. However, using generic failure data, which is usually subject to both aleatory and epistemic uncertainty, in BT may seriously undermine the accuracy and reliability of outcomes (likelihood of accident consequences) of safety assessment of process systems (Khakzad et al., 2013). In other words, in conventional applications of BT, usually crisp probabilities are being used, which are very challenging to estimate and prone to high uncertainties. As such, it is difficult for subject domain experts to express their judgment precisely using crisp numbers (assigning a single probability value to a basic event) (Yazdi and Zarei, 2018) particularly where well-structured databases do not exist. Therefore, despite its advantages, the application of crisp probabilities to assess uncertainty in BT has been blamed by several researchers (Aqlan and Mustafa Ali, 2014; Ferdous et al., 2012; Mohsendokht, 2017). Among different ways which have been proposed to tackle the drawbacks of using crisp probabilities, fuzzy set theory has been more popular (Zadeh, 1965).
Convectional fuzzy including triangular and trapezoidal membership functions have been commonly used in dealing with uncertainty arising from incomplete knowledge of experts (epistemic uncertainty). To address the epistemic uncertainty more effectively, the traditional fuzzy set was later developed into the Intuitionistic and Pythagorean fuzzy sets. These new sets include the membership and non-membership functions and hesitation margin groups. Several researchers have incorporated intuitionistic fuzzy sets into fault tree to risk

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and reliability analysis on chemical process systems (Chang et al., 2006; Cheng et al., 2009; Kumar and Yadav, 2012; Ming-Hung et al., 2006). As an example, Sayyadi Tooranloo and sadat Ayatollah, (2016) and Xu and Zhao, (2016) illustrated that Intuitionistic fuzzy set is an appropriate method to deal with uncertainties in FMEA and recommended that it can be useful in other risk assessment methods. Yazdi, (2018) used Intuitionistic fuzzy numbers (IFNs) in order to enhance the performance of risk matrix. Therefore, the model based on the 2-tuple linguistic terms (i.e., High = (0.81,0.87,0.93;0.79,0.87,0.95)) will be more flexible and precise to cope with expert judgments in the subjective acquisition process.
The present study is aimed at increasing the accuracy of BT outcomes by incorporating Intuitionistic fuzzy set into BT, developing a so-called fuzzy extended Bow tie (FEBT) model. The FEBT, compared with conventional fuzzy BT methods (CFBT) uses new the triangular IFNs, providing a more accurate cause-consequence model of accident scenarios while dealing more effectively with uncertainties arising from data scarcity and expert judgment ambiguity.

2. Developed Methodology

2.1 Bow ties (BT)

The Bow-tie (BT) is a powerful way of effectively communicating hazards, threats, consequences and controls of accident scenarios. BT diagram clearly displays the links between the potential basic events and intermediate events which contribute to an accident scenario as well as the possible consequences of the accident scenario according to work or failure of safety barriers. However, one of major concerns regarding BT is how failure data are derived to be used in the BT. There is much uncertainty in generic failure data, which is the most popular way to extract failure data, as well as in expert judgments as so to calculate probability of basic and top events, safety barriers, and consequently potential consequences. Fuzzy set theory is one of the solid approaches to tackle this problem. In the present study the IFNs are used to improve the accuracy of BT outcomes.

2.2 Fuzzy set theory and Expert Elicitation

Experts' estimations are an appropriate source of data in the case of absence or lack of sufficient objective failure data. Due to the increasing number of complex systems. Once elicitation process is properly finished, experts' opinions should be combined to acquire an aggregate approximation that can be used for reliability analysts. In the present study, the aggregation of experts' opinion is done in three steps: (i) obtaining qualitative terms of event occurrence based on expert knowledge (based on three experts, E1, E2, and E3), (ii) converting qualitative terms into the corresponding IFNs using Table 1, (iii) applying aggregation procedure under fuzzy environment using Equation 1.

Table 1: The linguistic terms and the corresponding IFNs (modified after (Kumar, 2019))

Linguistic terms	Corresponding IFNs
Very Low (VL)	(0.00,0.04,0.08;0.00,0.04,0.08)
Low (L)	(0.07,0.13,0.19;0.06,0.13,0.20)
Fairly Low (FL)	(0.17,0.27,0.37;0.15,0.27,0.39)
Medium (M)	(0.35,0.50,0.65;0.32,0.50,0.68)
Fairly High (FH)	(0.62,0.73,0.82;0.61,0.73,0.85)
High (H)	(0.81,0.87,0.93;0.79,0.87,0.95)
Very High (VH)	(0.92,0.96,1.00;0.92,0.96,1.00)

Considering a triangular IFN as $\widetilde{A} = (a, b, c; \acute{a}, b, \acute{c})$, and according to the weight of each expert, the similarity aggregation measure (SAM) procedure is applied in different steps provided by (Yazdi and Zarei, 2018) summarized in Equation (1)

$$\tilde{A}_{\text{aggregated}} = \sum_{m=1}^{M} W_m \otimes \tilde{A}_{\text{m}} \tag{1}$$

where $\tilde{A}_{\text{aggregated}}$ is aggregated fuzzy number, m is the number of experts, $\tilde{A}_{\text{m}}$ denotes the opinion of m-th expert in terms of IFN (per year), and W_m is the weight of the m-th expert.
The process of converting IFN to a single scalar quantity is called IF-defuzzification. The obtained failure possibility of each event can be defuzzified using the following formula to obtain a crisp possibility score (Kumar, 2019).

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

where X is the failure possibility of an event, which can be converted to failure probability of the event Onisawa's equation (Onisawa, 1988):

$$\mathrm{FPr} = \begin{cases} 1/10^{k} & FP \neq 0 \\ 0 & FP = 0 \end{cases}, k = 2.301 \times [(1 - FPs)/FPs]^{1/3} \quad (3)$$

Where K is a constant value, FPs is fuzzy possibility, and FPr is fuzzy probability for each event.
At the end, the obtained fuzzy probabilities are assigned as failure probabilities of the events and safety barriers in the developed BT model (Zarei et al., 2017).

3. Application of the methodology: A Case study

Metering and regulating stations are an integral part of the natural gas transmission and distribution systems. The metering and regulating stations reduce and regulate the downstream pressure, measure the quantity of energy transferred from the natural gas transmission system to the medium pressure networks or to consumers connected directly to the transmission system and add a distinctive odor to the natural gas for prompt detection of any gas leakage, as required by national and international safety standards. In the present study, the failure of a pressure regulating section (FPRS) is chosen as the most critical event in gas stations (Zarei et al., 2017).

4. Results and discussion

According to the BT model which was developed in (Zarei et al., 2017) to present a casual modeling of FPRS, experts' opinions along with the corresponding intuitionistic fuzzy aggregate and probabilities for 43 basic events (BEs) and safety barriers (IIB, DIB, Congestion, ESDa, ESDm) are shown in Table 2. A comparison of occurrence probabilities of basic event using both EFBT and CFBT is also presented in Figure1. As can be seen, occurrence probabilities obtained using EFBT are higher than those of CFBT. According to EFBT, the basic events 9 (Lack of permit request), 10 (Failure in permit implementation) and 14 (Tearing sleeve) have the highest occurrence probabilities, while according to CFBT the basic events 9, 26 (Closing gear to gear of pipes) and 10 are the likeliest events.

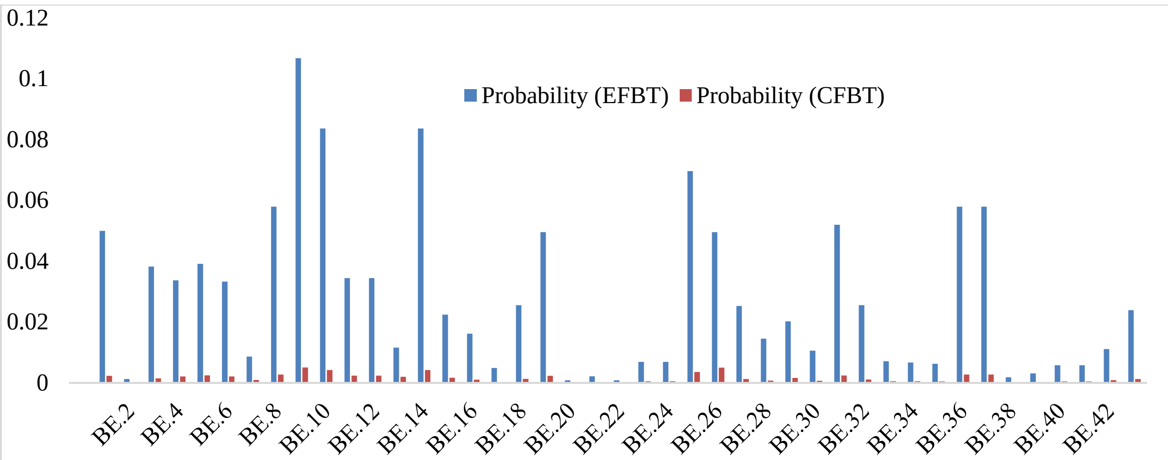

Figure 1: Occurrence probability of basic events using both EFBT and CFBT

Figure 2 compares the failure probabilities of the safety barriers using both extended (EFST) and conventional (CFST) fuzzy set theory, indicating that the failure probabilities using proposed fuzzy set theory are again higher. The differences can be explained in two ways.
Firstly, the employed IFNs include two sets of fuzzy triangular numbers which help more effectively deal with subjectivity of human being; Secondly, as pointed out in Yazdi and Zarei, (2018), different aggregation procedures can lead to considerably different results although the final critical components ranking would be same. Thus, the SAM aggregation procedure, which is used in the present study, because of its features such as reducing the effect of similar opinions from low weighted experts, can be identified as another reason for different results than those of CFBT.

Table 2: Experts' opinions along with intuitionistic fuzzy aggregated and probabilities of basic events and safety barriers

	Tag	Experts' opinions E1, E2, E3			Intuitionistic fuzzy aggregate	Possibility (using Eqs. 1-2)	Probability (using Eq. 3)
basic events	BE.1	FH	FH	H	(0.681,0.775,0.855;0.668,0.775,0.882)	8.47E-01	5.00E-02
	BE.2	VL	FL	M	(0.166,0.260,0.354;0.150,0.260,0.370)	3.33E-01	1.26E-03
	BE.3	FH	FH	FH	(0.620,0.730,0.820;0.610,0.730,0.850)	8.11E-01	3.83E-02
	BE.4	H	M	FH	(0.605,0.709,0.807;0.585,0.709,0.834)	7.92E-01	3.37E-02
	BE.5	VH	FH	M	(0.643,0.740,0.831;0.630,0.740,0.850)	8.14E-01	3.92E-02
	BE.6	H	FH	M	(0.603,0.707,0.806;0.583,0.707,0.832)	7.91E-01	3.33E-02
	BE.7	VH	VL	M	(0.450,0.525,0.600;0.440,0.525,0.610)	5.82E-01	8.67E-03
	BE.8	FH	VH	FH	(0.714,0.802,0.876;0.707,0.802,0.897)	8.66E-01	5.79E-02
	BE.9	VH	VH	FH	(0.824,0.886,0.942;0.820,0.886,0.952)	9.30E-01	1.07E-01
	BE.10	H	VH	FH	(0.783,0.853,0.917;0.773,0.853,0.933)	9.07E-01	8.37E-02
	BE.11	M	VH	FH	(0.615,0.718,0.814;0.601,0.718,0.835)	7.96E-01	3.45E-02
	BE.12	M	VH	FH	(0.615,0.718,0.814;0.601,0.718,0.835)	7.96E-01	3.45E-02
	BE.13	H	H	-	(0.550,0.590,0.631;0.536,0.590,0.645)	6.27E-01	1.16E-02
	BE.14	H	VH	FH	(0.783,0.853,0.917;0.773,0.853,0.933)	9.07E-01	8.37E-02
	BE.15	H	M	M	(0.519,0.636,0.753;0.492,0.636,0.779)	7.31E-01	2.25E-02
	BE.16	M	FH	M	(0.434,0.572,0.703;0.411,0.572,0.733)	6.80E-01	1.62E-02
	BE.17	FL	FL	FH	(0.315,0.418,0.515;0.298,0.418,0.538)	4.98E-01	4.93E-03
	BE.18	FH	M	FH	(0.536,0.658,0.767;0.519,0.658,0.797)	7.51E-01	2.56E-02
	BE.19	FH	H	FH	(0.679,0.774,0.854;0.666,0.774,0.881)	8.46E-01	4.96E-02
	BE.20	FL	FL	L	(0.138,0.225,0.312;0.121,0.225,0.329)	2.94E-01	8.30E-04
	BE.21	M	FL	L	(0.204,0.309,0.415;0.183,0.309,0.435)	3.93E-01	2.19E-03
	BE.22	FL	FL	L	(0.138,0.225,0.312;0.121,0.225,0.329)	2.94E-01	8.30E-04
	BE.23	FH	M	L	(0.359,0.465,0.564;0.343,0.465,0.588)	5.47E-01	6.92E-03
	BE.24	FH	M	L	(0.359,0.465,0.564;0.343,0.465,0.588)	5.47E-01	6.92E-03
	BE.25	H	H	FH	(0.749,0.825,0.895;0.732,0.825,0.918)	8.87E-01	6.96E-02
	BE.26	FH	H	FH	(0.679,0.774,0.854;0.666,0.774,0.881)	8.46E-01	4.96E-02
	BE.27	FH	FH	M	(0.533,0.656,0.765;0.517,0.6560.795)	7.49E-01	2.53E-02
	BE.28	FH	FH	FL	(0.475,0.582,0.675;0.462,0.582,0.702)	6.63E-01	1.45E-02
	BE.29	M	H	M	(0.494,0.616,0.737;0.467,0.616,0.764)	7.15E-01	2.02E-02
	BE.30	FH	L	FH	(0.448,0.543,0.623;0.438,0.543,0.647)	6.13E-01	1.06E-02
	BE.31	H	FH	FH	(0.690,0.781,0.860;0.676,0.781,0.887)	8.52E-01	5.20E-02
	BE.32	FH	M	M	(0.536,0.658,0.767;0.519,0.658,0.797)	7.51E-01	2.56E-02
	BE.33	FH	L	M	(0.362,0.469,0.569;0.345,0.469,0.592)	5.51E-01	7.11E-03
	BE.34	M	L	FH	(0.349,0.458,0.561;0.332,0.458,0.585)	5.43E-01	6.71E-03
	BE.35	M	M	FL	(0.292,0.426,0.560;0.265,0.426,0.587)	5.33E-01	6.29E-03
	BE.36	FH	VH	FH	(0.714,0.802,0.876;0.707,0.802,0.897)	8.66E-01	5.79E-02
	BE.37	FH	VH	FH	(0.714,0.802,0.876;0.707,0.802,0.897)	8.66E-01	5.79E-02
	BE.38	L	FL	M	(0.191,0.293,0.394;0.172,0.293,0.414)	3.73E-01	1.84E-03
	BE.39	FL	FL	M	(0.228,0.344,0.460;0.205,0.344,0.483)	4.37E-01	3.13E-03
	BE.40	FL	M	M	(0.284,0.416,0.547;0.258,0.416,0.574)	5.21E-01	5.79E-03
	BE.41	FL	M	M	(0.284,0.416,0.547;0.258,0.416,0.574)	5.21E-01	5.79E-03
	BE.42	M	M	M	(0.350,0.500,0.650;0.320,0.500,0.680)	6.20E-01	1.11E-02
	BE.43	M	FH	FH	(0.521,0.646,0.758;0.504,0.646,0.788)	7.41E-01	2.39E-02
Safety barriers	IIB	FH	FH	M	(0.533,0.656,0.765;0.517,0.656,0.795)	7.49E-01	2.53E-02
	DIB	VH	VH	VH	(0.920,0.960,1.000;0.920,0.960,1.000)	9.87E-01	2.83E-01
	Congestion	M	FL	M	(0.294,0.428,0.563;0.267,0.428,0.589)	5.36E-01	6.40E-03
	ESDa	M	M	FH	(0.437,0.574,0.705;0.413,0.574,0.735)	6.81E-01	1.64E-02
	ESDm	FH	M	M	(0.449,0.584,0.712;0.426,0.584,0.742)	6.90E-01	1.73E-02

IIB; Immediate ignition barrier, DIB; Delay ignition barrier, ESDa; Automatic emergency shutdown, ESDm; Manual emergency shutdown

Table 3: Probability results for main contributing intermediate events and consequences

Events and consequences		Probability (EFBT)	Probability* (CFBT)
Critical event of the BT	Failure of pressure regulating section (FPRS)	5.69E-01	4.73E-02
Main contributing failures	Human failures	4.16E-01	2.80E-02
	Mechanical Failures	1.84E-01	1.36E-02
	Process failures	9.54E-02	6.23E-03
Potential consequences	C1: Safe minor release	5.60E-01	4.72E-02
	C2: Near miss	6.40E-03	6.04E-05
	C3: Moderate material loss	2.51E-03	3.97E-07
	C4: Minor flash fire	1.62E-05	2.50E-08
	C5: Minor VCE	1.12E-04	6.46E-08
	C6: Major material loss	4.41E-05	5.12E-10
	C7: Catastrophic VCE	2.84E-07	3.23E-11
	C8: Moderate jet fire	2.31E-04	6.51E-08
	C9: Catastrophic jet fire	4.07E-06	8.41E-11

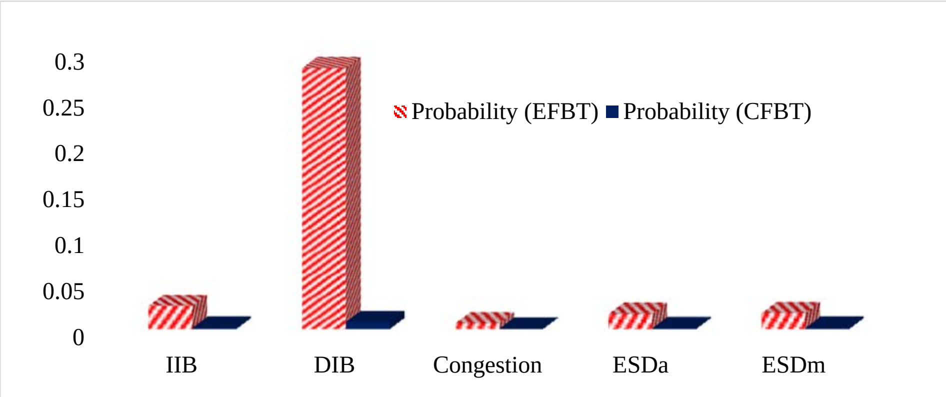

Figure 2: Comparison of failure probability for safety barriers using EFST and CFST

A comparison of results regarding occurrence probability of the top event (FPRS), its main contributing factors, including human failures, mechanical failures and process failures, and potential consequences of the accident scenario is shown in Table 3. Occurrence probability of FPRS by EFBT and CFBT approaches are 1.64E-02 and 1.07E-03, respectively, showing a difference of an order of magnitude. Fuzzy set theory only considers membership degree and is not perfect in expressing the fuzziness of a rule-based expert system (Zadeh, 1965). Thus, it is not completely justifiable or technically sound to quantify grades of membership and non- by using an exact numeric value in human cognitive activities. In contrast, the concept of intuitionistic fuzzy sets, characterized by membership and non-membership functions whose values are intervals, is more accurate for handling uncertain and imprecise information in expert systems (Atanassov, 1986). Human, mechanical and process failures are recognized as the main contributing events which directly result in occurrence of the accident scenario. The results in both approaches revealed that human failure has the highest and process failures has the lowest occurrence probability (Table 3). Therefore, human failure can be considered the most critical event causing the critical event of the BT. Occurrence probabilities of potential consequences also shown in Table 3. Accordingly, C1 and C2 are recognized as the most probable consequences among nine potential consequences.

4. Conclusion

In the present study, a comparison was made between the intuitionistic fuzzy numbers and conventional fuzzy numbers by applying them to bow-tie diagram to model uncertainty. The results of the two fuzzy approaches show a significant difference in terms of outcome probabilities. The difference is because of comprehensiveness of intuitionistic fuzzy theory by considering the membership, non-membership functions and n more hesitation margin groups compared to the conventional fuzzy theory consisting of only the membership functions and a method of aggregation. In this regards, it can be concluded that the obtained results by intuitionistic fuzzy numbers are more accurate though more validation is required.

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