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A Short Comunication

A Question on Using Fuzzy Set Theory and Its Extensions in Safety and Reliability

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Keywords

Fuzzy set theory,
Experts' judgment,
Subjective uncertainty.

Abstract

In order to analyze the safety and reliability of a system, different types of probabilistic structural methods such fault tree analysis (FTA), event tree analysis (ETA), Bayesian Network (BN) can be used. In such probabilistic methods, the failure probability of an event as root events must be obtained. Reliability Data handbook database can be used to obtain the failure probability of the events. However, in some case, there is no data about the failure probability of event. In such a case, expert judgment using fuzzy set theory and its extensions are utilized as an alternative in order to deal with the subjective uncertainty. However, the common existing expert judgment approaches still suffer from the logical lack of reliability in the experts' opinions elicitation procedure. This paper analyzes the use of fuzzy set theory and its extensions in safety and reliability analysis as well as discussing how they suffer from lack of reliability As a result, it should make researchers in that situation deeply think about finding out of a better alternative using experts' judgment-based methods.

1. Introduction

The fuzzy set theory and its extension such as to intuitionistic Pythagorean fuzzy set have been widely used in literature but not limited following references [1–9]. Recently, Yazdi et al. reviewed uncertainty handling in fault tree based risk assessment and the proposed future perspective [10]. According to this study, a combination of Bayesian Network and fuzzy set theory can better reflect experts' opinions. Inspired by the PRISRMA (preferred reporting items for systematic reviews and meta-analysis) [11,12], a bibliometric analysis was performed concerning the number of papers published per year by the end of July 2020. The idea behind of this bibliometric analysis was to make a clear distribution of both the published papers in different groups and the existing research trends in the field of safety and reliability analysis using fuzzy set theory, which can provide valuable understanding of the decision-making problems for researchers working in this field. Figure 1 demonstrates that safety and reliability analysis using fuzzy set theory and its several development methods are commonly utilized in different domains, predominantly "Engineering electrical electronic" (101 papers, 26.1%), "Computer science artificial intelligence" (64 papers, 16.5%), "Engineering multidisciplinary" (47 papers, 12.1%), "Computer science theory methods" (32 papers, 8.1%), "Computer science information systems" (29 papers, 7.9%), and more.

Figure 2 illustrates that the number of publications on safety and reliability analysis using fuzzy set theory and its several development methods has increased since 2014. This trend saw the highest increase in 2019. According to this point, it is projected that the emergency decision-making used in different studies will continue to grow in the coming decade.

In Table 1, the relevance of the recently published works is related to safety and reliability analysis using fuzzy set theory and its several development methods. By thoroughly reviewing the emergency decision-making concept and its relevant applications, it is clear that safety and reliability analysis using fuzzy set theory still requires further development and improvement from different viewpoints, particularly the uncovered lack of the original form. The aforementioned reason motivated the author to question the safety and reliability analysis using fuzzy set theory approaches and cope with the uncovered drawbacks.

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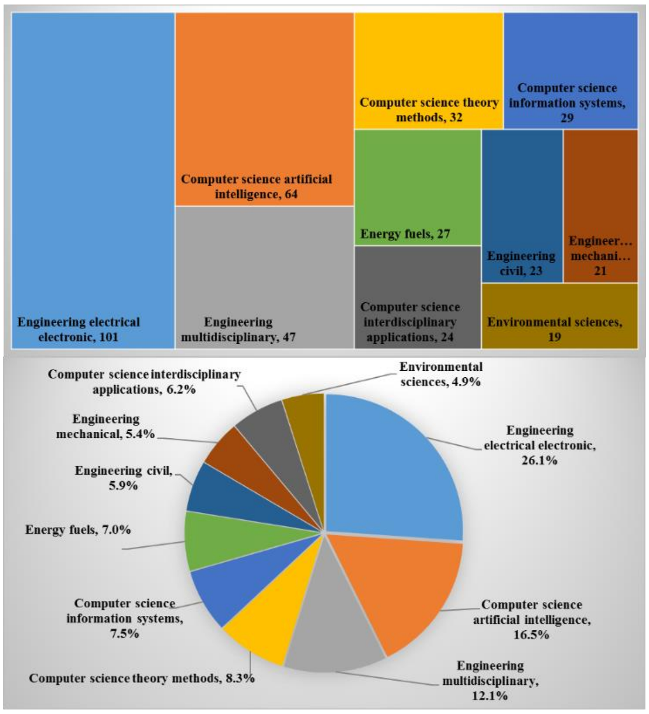

Figure 1. Distribution of published works according to the different application areas by the end of year July 2020 in the area of safety and reliability analysis using fuzzy set theory and its several development methods **(**source: Web of Science, keywords search: (Title: "fuzzy set theory" AND "reliability"))

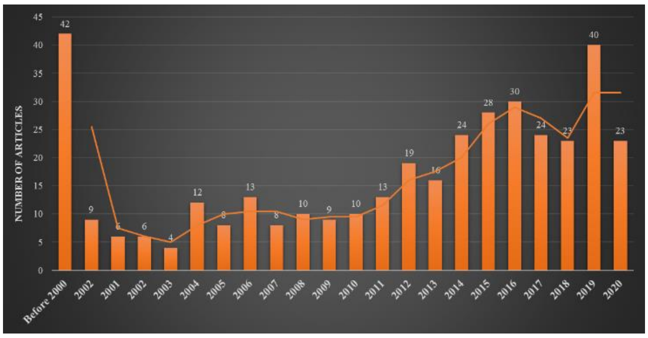

Figure 2. Distribution of published works according to year by the end of year July 2020 in the area of safety and reliability analysis using fuzzy set theory and its several development methods (source: Web of Science, keywords search: (Title: "fuzzy set theory" AND "reliability"))

In the next section, a description of fuzzy set theory and its extensions is provided, which helps ask a critical question about why all fuzzy based methods still suffer from lack of reliability.

2. Progress of Fuzzy Set Theory in the Field of Safety and Reliability Analysis

In this section, the progress of fuzzy set theory in the field of safety and reliability analysis over a period of time is explained. To clearly understanding of how fuzzy set theory and its extensions are utilized in safety and reliability analysis, assume that, in an FTA, there are three basic events. In order to obtain the failure probability of each basic events, only three independent experts with relevant experiences and expertise are employed. Each expert expresses his/her opinions about failure probability in qualitative terms. Once all opinions are collected, the qualitative terms are transferred into the fuzzy numbers. According to different types of fuzzy numbers and considering the importance weight of experts, several aggregation processes will be used. Therefore, different types of aggregation process will introduce different results.

In the following, the preliminaries of fuzzy set theory as well as its extension are reviewed.

(i) Triangular and trapezoidal fuzzy set [47,48]:

The membership function can be defined both trapezoidal and triangular fuzzy numbers as follows:

a) In triangular form, $\tilde{A} = (a_1, a_2, a_3)$

$$V_i(x) = \begin{Bmatrix} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2 \\ \frac{a_3-x}{a_3-a_2}, & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{Bmatrix}$$

b) In trapezoidal form, $\tilde{A} = (a_1, a_2, a_3, a_4)$

$$V_i(x) = \begin{Bmatrix} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2 \\ 1, & a_2 \le x \le a_3 \\ \frac{a_4-x}{a_4-a_3}, & a_3 \le x \le a_4 \\ 0, & x > a_4 \end{Bmatrix}$$

The corresponding translation of triangular and trapezoidal fuzzy set into fuzzy numbers are provided in Table 2.

Table 2. Fuzzy numbers of conversion scale six

Linguistic Expressions	Fuzzy Numbers
Very low (VL)	(0,0,0.1,0.2)
Low (L)	(0.1,0.25,0.25,0.4)
Medium (M)	(0.3,0.5,0.5,0.7)
High (H)	(0.6,0.75,0.75,0.9)
Very High (VH)	(0.8,0.9,1,1)

Suppose that each expert, E_j (k = 1, 2, . . ., n) states his attitude about a certain feature in a specific context by a predefined set of linguistic variables. The linguistic expressions can be transferred to the corresponding fuzzy numbers. The procedure is explained in detail in what follows:

1. Computing the degree of similarity (degree of agreement). $S_{uv}(\tilde{R}_u, \tilde{R}_v)$ is defined as opinions between each pair of experts E_u and E_v. According to this consideration for $S_{uv}(\tilde{R}_u, \tilde{R}_v)$ when $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3,)$ are two standard triangular fuzzy numbers, then the degree of agreement function of S is defined as:

$$S(\tilde{A}, \tilde{B}) = 1 - \frac{1}{J}\sum_{i=1}^{J}|a_i - b_i| \quad (1)$$

When $S(\tilde{A}, \tilde{B}) \in [0, 1]$, the greater value of S $(\tilde{A},\tilde{B})$ is the best similarity between two fuzzy numbers of $\tilde{A}$ and $\tilde{B}$.

Moreover, the amount of J is 3 and 4 for triangular and trapezoidal fuzzy number respectively.

2. Next it is computing the Average of Agreement (AA) degree $AA(E_u)$ of the expert's opinions.

$$AA(E_u) = \frac{1}{J-1}\sum_{\substack{u \neq v \\ v=1}}^{J} S(\tilde{R}u, \tilde{R}v) \quad (2)$$

3. Computing the Relative Agreement (RA) degree, $RA(E_u)$ of the experts.

$$E_u(u = 1,2, \dots, J) \quad as \quad RA(E_u) = \frac{AA(E_u)}{\sum_{u=1}^{J} AA(E_u)} \quad (3)$$

4. Estimate the Consensus Coefficient (CC) degree, $CC(E_u)$ of expert's opinions, $E_u(u = 1, 2, \dots, J)$:

$$CC(E_u) = \beta \cdot W\,(E_u) + (1-\beta) \cdot RA\,(E_u) \quad (4)$$

where $W\,(E_u)$ is the weight of each expert and the term is β is nominated as a relaxation factor of the offered procedure due to $\beta(0 \leq \beta \leq 1)$. It illustrates the importance of W (E_u) over RA (E_u). When β = 0, no weight has been given to it by experts and thereby a homogenous group of experts should be employed whereas when β = 1, signifies that the consensus degree of an expert is equal to its importance weight.

5. Finally, the aggregated result of the experts' judgment $\tilde{R}_{AG}$, could be found out as follows:

$$\tilde{R}_{AG} = CC(E_1) \otimes \tilde{R}_2 \oplus CC(E_2) \otimes \tilde{R}_2 \oplus \dots \oplus CC(E_m) \otimes \tilde{R}_M \quad (5)$$

where sign ⊕ is fuzzy addition and ⊗ is fuzzy scalar multiplication operator. Additionally [49] represented that the fuzzy operations of trapezoidal fuzzy member are trapezoidal fuzzy member.

2.1. Defuzzification Procedure

Defuzzification procedure is a quantifiable outcome of Fuzzy theory according to process of making.

$$X^* = \frac{\int v_i(x)xdx}{\int v_i\,(x)dx} \quad (6)$$

where

X^*= Defuzzified output;

$v_i(x)$ = Aggregated membership function;

x = output variable.

(ii) Intuitionistic fuzzy set (IFS) [50]

Atanassov (1986) [51] presented Intuitionistic fuzzy set (IFS) to deal acceptably with ambiguity as an extension of the classical model introduced by Zadeh (1965) [52] which includes the membership and non-membership functions and hesitation margin groups.

Definition 1. Considering X as a fixed set, intuitionistic fuzzy S in X is introduced:

$$S = \{\langle x,\ \mu_S(x), \nu_S(x)\rangle \,|x \in X\}, \quad (7)$$

where $\mu_S(x)$ and $\nu_S(x) \in [0,1]$ are denoted as a degree of membership and non-membership functions, respectively, and satisfy $0 \leq \mu_S(x)+\nu_S(x) \leq 1, \forall x \in X$.

In addition, the hesitation degree of $x \in S$ indicates the degree of uncertainty of x to S and is given as $\pi_S(x) = 1 - \mu_S(x) - \nu_S(x)$, and clearly satisfies $0 \leq \pi_S(x) \leq 1,\ \forall x \in X$.

The set $(\mu_S(x), \nu_S(x))$ is called an intuitionistic fuzzy number in IFS and $\alpha = (\mu_S(x), \nu_S(x))$ simply represents each IFN, where $\mu_\alpha \in [0,1]$ and $\nu_\alpha \in [0,1]$, and also satisfies $\mu_\alpha + \nu_\alpha \leq 1$. It should be noted that for an IFN $\alpha = (\mu_\alpha,\ \nu_\alpha)$, $\alpha^+(1,0)$ and $\alpha^-(0,1)$ are nominated as the largest and smallest IFNs, respectively.

Definition 2. Let $\alpha_1 = (\mu_{\alpha_1}, \nu_{\alpha_1})$ and $\alpha_2 = (\mu_{\alpha_2}, \nu_{\alpha_2})$ be two IFNs, and the intuitionistic fuzzy distance (IFD) between α_1 and α_2 is illustrated as follows:

$$d_{IFD}(\alpha_1, \alpha_2) = |\alpha_1 - \alpha_2| = \tfrac{1}{2}\left(|\mu_{\alpha_1} - \mu_{\alpha_2}| + |\nu_{\alpha_1} - \nu_{\alpha_2}|\right) \quad (8)$$

The next stage of the procedure presents the aggregation of experts' opinions in an intuitionistic fuzzy environment.

Aggregate the expert's opinion using the intuitionistic fuzzy weighted averaging (IFWA) operator for any basic events, $\text{BE}_i = (i = 1, \dots, m)$.

$$\alpha_{ij} = IFWA(\alpha_{ij}^1, \alpha_{ij}^2, \dots, \alpha_{ij}^n) = \sum_{k=1}^{n} \lambda_k\, \alpha_{ij}^k$$

$$= \left[1 - \prod_{k=1}^{n}(1-\mu_{ij}^k)^{\lambda_k}, \prod_{k=1}^{n}(\nu_{ij}^k)^{\lambda_k}\right] \quad (9)$$

where $\alpha_{ij} = (\mu_{ij}, \nu_{ij})$ is the final aggregated subjective opinions in terms of IFN,

$\alpha_{ij}^k = (\mu_{ij}^k, \nu_{ij}^k)$ is the IFN that is transferred by the corresponding linguistic terms according to an experts' opinion

λ_k is the given weight to each expert represents the importance of his/her opinion on BE_i, and satisfies $\lambda_k > 0$ $(k = 1, \dots, n)$ and $(\sum_{k=1}^{n} \lambda_k = 1)$.

Next, to make reliable decisions with consideration of maintenance actions, the intuitionistic fuzzy output is converted into the crisp value using Eq (13). However, Boran et al. (2009) [53] showed that Eq 14 can be normalized to (15). Additionally, Anzilli and Facchinetti, (2016) [54] represented that, Eq 15 can be considered as a defuzzification IFNs which obtained by:

$$Val_S(x) = \tfrac{1}{2} \times \left(1 + \mu_S(x) - \nu_S(x)\right) \quad (10)$$

(iii) Pythagorean Fuzzy Sets (PFS) [55]

Table 1. The recently published papers are not limited to (source: Web of Science, keywords search: (source: Web of Science, keywords search: (Title: "emergency decision-making" OR "emergency decision making"))

Reference	Highlights
Markowski et al. [6]	All input variables are substituted with fuzzy numbers; after utilizing fuzzy arithmetic process, the probability of TE is then computed.
Ferdous et al. [13]	Proposed an approach for a fuzzy based analysis using computer and fault tree tools.
Celik et al. [14]	Proposed integration of FFTA into a shipping accident investigation (SAI)
Mechri et al. [15]	Assessing the performance of SIS with consideration of CCF. Accepting decision makers to share their opinions about uncertainty of CCF values.
Mentes and Helvacioglu [16]	Proposed a methodology integrating the effects of human errors and operational failures in fuzzy environment.
Shahriar et al. [17]	Explored both subjective uncertainty and interdependencies among BEs.
Aqlan and Mustafa Ali [18]	Introduced an approach for risk analysis of a lean manufacturing system using FFTA in one part.
Shi et al. [19]	Proposed a methodology based on FFTA which was improved by AHP.
Chen [91]	Hazard analysis of man–machine-environment system is improved by engaging a fuzzy causal model.
Omidvari et al. [21]	Application of fuzzy logic is utilized to obtain the subjective opinions of expert for each BE and computing the probability of TE.
Martorell et al. [22]	Proposed a method for assessment of risk impacts using FTA based on different confidence level of probability of BEs.
Lavasani et al. [23]	The proposed model focuses on risk assessment of leakage in a typical offshore well using an extension of FFTA.
Ramzali et al. [24]	The proposed model used fuzzy set theory to combine experts' knowledge as an input probability for FTA.
Lavasani et al. [25]	The proposed model used fuzzy set theory to combine experts' knowledge as an input probability for FTA.
Duan et al. [8]	Proposed a model to estimate the risk of identified hazards according to risk matrix. FFTA is used for handling the likelihood factor of risk matrix in this regards.
Ahn and Chang [26]	Proposed a model to calculate risks according to the ratio obtained from variables of an event using fuzzy modelling system.
Yan et al. [27]	Proposed a model to compute the probability of TE based on fuzzy probability. BN is used for mapping FT and considering the dependency uncertainty between BE.
Wang et al. [28]	Proposed a hybrid approach engaging fuzzy set theory which constructs a perfect judgment reliance by giving perception into the uncertainties.
Mohsendokht [29]	The proposed model used fuzzy set theory to obtain probability of each basic event failure as input to the probability calculation of UF_6 release.
Sahin [30]	Proposed a framework to control consistency linked with the consistency of employed experts by prioritization straightforward fuzzy inputs as basic events given to the FTA.
Yazdi et al. [31]	Proposed a framework to compute probability of TE using fuzzy set theory with consideration of dependency between each BE according β factor method.
Yazdi [32]	Proposed a framework to compute probability of TE using fuzzy set theory and fuzzy AHP to obtain more realistic result.
Yazdi and Kabir [33]	Proposed an approach due to risk analysis in chemical process industries considering uncertainty conditions and dependency of basic event utilizing fuzzy logic and Bayesian network, respectively.
Jiang and Wang [34]	Introduced a framework according to fuzzy logic in order to cope with imprecise expert judgement in FTA.
Yazdi and Zarei [35]	Proposed a framework to estimate the basic event probability in FTA using several applications of fuzzy logic. The results of different methods are compared and the advantages and disadvantages are discussed.
Yazdi et al. [36]	Proposed a framework to compute the probability of TE using FFTA and fuzzy modified TOPSIS to obtained effectiveness reduction of TE probability.
Yazdi and Soltanali [37]	Proposed a framework using intuitionistic fuzzy set to compute the probability of TE.
Yazdi [38]	Proposed a framework using intuitionistic fuzzy set theory to estimate basic events and top event probability.
Yazdi and Kabir [39]	Proposed an approach for risk analysis in chemical process industries considering uncertain conditions and dependency of basic event utilizing fuzzy logic, evidence theory, and Bayesian network.
Yazdi et al. [40]	Proposed a framework to compute the probability of TE using fuzzy FTA with consideration of confidence level.
Yazdi et al. [41]	Proposed a framework to compute the probability of TE using intuitionistic fuzzy FTA.
Zarei et al. [42]	Proposed a framework to compute the probability of TE using intuitionistic fuzzy FTA.
Zarei et al. [43]	Developing a Fuzzy Bayesian Network (FBN) methodology to deal more effectively with uncertainty
Yazdi [44]	A heuristic approach to enhance the reliability of system safety assessment is introduced.
Yazdi [45]	A perceptual computing–based method to prioritize intervention actions in the probabilistic risk assessment techniques is introduced.
Kabir et al. [46]	A method for temporal fault tree analysis using intuitionistic fuzzy set and expert elicitation is introduced.

In literature [56–59], Yager provided three basic representations for Pythagorean membership grades. The first one is (a, b) satisfying the conditions that $\in [0,1]$, $b \in [0,1]$ and $a^2 + b^2 \leq 1$. The second one is the polar coordinates(r, θ) satisfying the conditions that $\in [0,1]$ and $\theta \in [0, \pi/2]$. The third one is (r, d) close to the second one satisfying the conditions that $r \in [0,1]$, $d \in [0, \pi/2]$, and $d = 1 - 2\theta/c$. Their relationship is that $a^2 + b^2 = r^2$,

$a = rcos(\theta)$, and $b = r\,sin(\theta)$. He referred to a fuzzy subset having these Pythagorean membership grades as a PFS. Similar to the definition of IFSs, in the following, we introduce the general definition of PFSs.

Let a set X be a universe of discourse. A PFS, P is an object having the form

$$P = \{< x, P(\mu_P(x), \nu_P(x)) > | x \in X\} \quad (11)$$

where the function $\mu P : X \rightarrow [0, 1]$ defines the degree of membership and $\mu_P: X \rightarrow [0, 1]$ defines the degree of non-membership of the element $x \in X$ to P, respectively, and for every $x \in X$, it holds that:

$$(\mu_P(x))^2 + (\nu_P(x))^2 \leq 1 \quad (12)$$

For any PFS, P and $x \in X$, $\pi_P(x) = \sqrt{1 - \pi_P^2(x) - \nu_P^2(x)}$ is called the degree of indeterminacy of x to P. For simplicity, we call $P(\mu_P(x), \nu_P(x))$ a Pythagorean fuzzy number (PFN) denoted by $\beta = P(\mu_\beta, \nu_\beta)$, where μ_β and $\nu_\beta \in [0,1]$, $\pi_\beta = \sqrt{1 - {\mu_\beta}^2 - {\nu_\beta}^2}$, and ${\mu_\beta}^2 + {\nu_\beta}^2 \leq 1$.

Given three PFNs $\beta_1 = P(\mu_{\beta_1}, \nu_{\beta_1})$, $\beta_2 = P(\mu_{\beta_2}, \nu_{\beta_2})$ and $\beta = P(\mu_\beta, \nu_\beta)$, Yager

In order to to aggregate PFNs, Yager [58] introduced the following weighted averaging aggregation operator.

Let $\beta_j = P(\mu_{\beta_1}, \nu_{\beta_1})(j = 1,2, \dots, n)$ be a collection of FPNs and $w = (w_1, w_2, \dots, n)^T$ be the weight vector of β_j, where w_j indicates the importance degree of β_j, satisfying $w_j \geq 0$ and $\sum_{j=1}^{n} w_j = 1$, and let Pythagorean fuzzy weighted averaging (PFWA): $\Theta^n \rightarrow \Theta$ if

$$PFWA = (\beta_1, \beta_2, \dots, \beta_n) = (\sum_{j=1}^{n} w_j\, \mu_{\beta_j}, \sum_{j=1}^{n} w_j\, \nu_{\beta_j})$$
(13)

Same as IFNs, the aggregation process can be done using (12).

These descriptions are only four types of fuzzy numbers. While there are more types, such as D numbers, rough set, cognitive set, spherical set, picture set, and so on, only those mentioned are considered in this paper. In the next section, a discussion is conducted to find out a much more appropriate way to deal with subjective opinions collected from expert judgment.

All papers will take evaluation process in the referee committee. For a paper to be considered for evaluation process, the author should submit his/her full length paper in .docx and .pdf formats. Please include all relevant materials (text and accompanying figures) into a single document.

The acceptance or rejection of the received manuscripts will be informed to the corresponding author and can be tracked by all authors through the journal web site. A paper which receives final or conditional acceptance, should be prepared regarding the requested corrections, and the revised manuscript should be resubmitted via the journal web site.

3. Discussion and Conclusion

In literature, there are some studies that deal with subjective judgments by experts like [60]. Different methods like using BN, fuzzy inference, etc., can be utilized to treat expert judgment. By reviewing state of arts, Yazdi et al. [10] proposed that a combination of BN and fuzzy set theory can provide proper treatment of subjective uncertainty. This suggests that different types of fuzzy numbers provide different results, which further causes decision makers to make more wrong decisions. If we assume that the triangular and trapezoidal fuzzy set are old numbers, after that Intuitionistic and Pythagorean fuzzy set were introduced to say that, they have better deal with the subjective uncertainty. However, by looking at the detail's explanations of D numbers, picture, spherical, rough, etc., set, we will see all have appropriate and logical steps to aggregate experts' opinions. In addition, there are many aggregation procedures which are out scope of this short combination. Thus, if all fuzzy sets are logical, it obscures the proper choice for our safety and reliability problem, the authors think that we surely cannot do such since more extensions have been introducing by scholars over time, which can be used to treat subjective uncertainty. Using the reliability and feasibility of fuzzy set theory and its extensions in such problems contains many ambiguities. Therefore, we need to find out how we can move forward from fuzzy set theory, at least providing a confidence level of using experts' judgments. How we can consider the confidence level. Probability?. As a direction for future study, expert judgment should be translated into probability in a proper way to see how it works. In addition, it can be intefrated with some methods such as but not limited to [61-83].

Conflict of Interest Statement

The authors declare no conflict of interest.

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