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Review

Fuzzy probability on reliability study of nuclear power plant probabilistic safety assessment: A review

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ABSTRACT

Fault tree analysis (FTA) is a graphical model which has been widely used as a deductive tool for nuclear power plant (NPP) probabilistic safety assessment (PSA). The conventional one assumes that basic events of fault trees always have precise failure probabilities or failure rates. However, in real-world applications, this assumption is still arguable. For example, there is a case where an extremely hazardous accident has never happened or occurs infrequently. Therefore, reasonable historical failure data are unavailable or insufficient to be used for statistically estimating the reliability characteristics of their components. To deal with this problem, fuzzy probability approaches have been proposed and implemented. However, those existing approaches still have limitations, such as lack of fuzzy gate representations and incapability to generate probabilities greater than 1.0E-3. Therefore, a review on the current implementations of fuzzy probabilities in the NPP PSA is necessary. This study has categorized two types of fuzzy probability approaches, i.e. fuzzy based FTA and fuzzy hybrid FTA. This study also confirms that the fuzzy based FTA should be used when the uncertainties are the main focus of the FTA. Meanwhile, the fuzzy hybrid FTA should be used when the reliability of basic events of fault trees can only be expressed by qualitative linguistic terms rather than numerical values.

1. Introduction

Fault tree analysis (FTA) has been widely used as a deductive tool for probabilistic safety assessment (PSA) to evaluate the performance of the safety systems of nuclear power plants (NPPs) in relation to potential initiating events that can be caused by random component failures, human errors, internal and external hazards (Yuhua and Datao, 2005; Hadavi, 2008; Dhillon, 2005; Stacey, 2007; Ericson, 2005; Guimaraes and Lapa, 2008). It can provide a comprehensive and structured approach to identify and understand key plant vulnerabilities by developing accident scenarios. Since designers, utility and regulatory personnel will use its results to verify NPP designs, to propose possible changes to the design and to the plant licensing basis (Liu et al., 2008; Delaney et al., 2005), it is therefore necessary to apply reliability data which are specific to the plant being evaluated. This data can be taken from operator and maintenance logs. It is also important to remember that the more data corresponds to the actual components of the plant being evaluated, the more useful it is and the more realistic the results of the PSA will be. Where the results indicate that changes could be realized to the design or operation of the plant to reduce risk, the changes should be incorporated where reasonably achievable.

In conventional FTA, basic events are always assumed to have precise probability distributions of their lifetime to failure. However, in real-world applications such as NPPs, this assumption is still arguable. When an accident has never happened or occurs infrequently, there will be insufficient historical failure data to probabilistically estimate the reliability characteristics of their safety system components. Consequently, to perform FTA, safety analysts have to utilize generic data, which may be taken from other nuclear industries and non-nuclear industries (Hsu and Musicki, 2005; Abdelgawad et al., 2010). However, since the used data are not comprehensive into the plant under investigation, generic data will add further uncertainty and imprecision to the results of the analysis (Abdelgawad et al., 2010; Song et al., 2009; Chin et al., 2009). Moreover, the results will not show the real performance of the safety systems of the NPP being evaluated (NEA, 2005).

Fuzzy set theory was firstly introduced as a useful tool to complement conventional reliability theories in 1989 (Onisawa, 1989). Since then, there have been a number of researchers

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tempted to develop techniques involving fuzzy set theory to evaluate system reliabilities. In the meantime, the concept of fuzzy probabilities which is represented by the membership functions of fuzzy numbers has been applied to study the reliability of safety systems of NPPs. However, the current implementations still have limitations, such as the unavailability of the corresponding fuzzy gates for exclusive OR and priority AND gates which may be involved in a complex fault tree analysis or the incapability to generate probabilities which are greater than 1.0E-3. Therefore, a review on the current implementations of fuzzy probabilities to characterize the reliability of components of NPP safety systems is necessary. The present paper is intended to review and discuss the current implementations of fuzzy probabilities in NPP PSA. The rest of the paper is organized as follows. Section 2 briefly describes fault tree analysis. The concepts of fuzzy sets and fuzzy numbers are briefly given in Section 3. In Section 4, the current implementations of fuzzy probabilities in NPP PSA are reviewed and discussed. Finally, the paper is summarized in Section 5.

2. Fault tree analysis

A fault tree is a graphical model representing the combinations of parallel and/or sequential fault events that can lead to the occurrence of the predefined undesired top event (Ericson, 2005). It depicts logical interrelationships amongst basic events to the top event using Boolean gates. To draw a fault tree, the process starts from the higher faults to the more basic faults. The output of two or more independent input events combined by an OR gate and by an AND gate as shown in Fig. 1 are calculated using (1–2), respectively (Ericson, 2005; Yang, 2007; Verma et al., 2010; IAEA, 2007).

In Fig. 1(a), the undesired top event A_0 will fail if all input events A_i fail together at the same time. On the other hand, in Fig. 1(b), the top event A_0 will fail if one of input events A_i fails.

$$P(A_0) = 1 - \prod_{i=1}^{n}\{1 - P(A_i)\} \quad (1)$$

$$P(A_0) = \prod_{i=1}^{n} P(A_i) \quad (2)$$

where $P(A_i)$ is the probability of the event A_i and n is the number of input events.

3. Fuzzy set theory

As opposed to the classical set theory in which the membership of elements in a set is assessed in binary terms – an element either belongs or does not belong to the set, fuzzy set theory allows an element in the set to have gradual assessment of its membership in the real unit interval [0,1] (Zadeh, 1965).

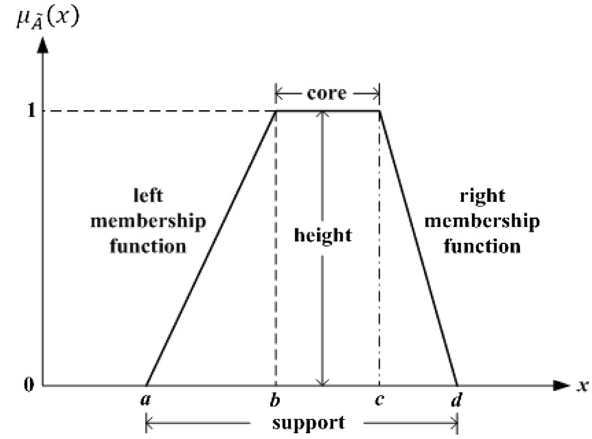

Fig. 2. Fuzzy number properties.

Let X be a collection of object universe whose elements are denoted by x. A fuzzy subset A in X is characterized by its membership function $\mu_A(X)$. This function associates with every single element x in X in the interval [0,1] as denoted in (3).

$$\mu_A : X \to [0, 1], x \mapsto \mu_A(x)\varepsilon[0, 1] \quad (3)$$

The value of the membership function $\mu_A(X)$ represents the membership grade of x in X. The closer the value to 1 is, the stronger the degree of membership of x in A is. On the other hand, the closer the value to 0 is, the weaker the degree of membership of x in A is.

Meanwhile, a fuzzy number is a special type of fuzzy sets whose membership functions are convex and normalized. The membership function of fuzzy numbers $\mu_{\tilde{A}}(x)$ can be expressed as follows.

$$\mu_{\tilde{A}}(x) = \begin{cases} \mu_{\tilde{A}}^{L}(x), & a \le x \le b \\ 1, & b \le x \le c \\ \mu_{\tilde{A}}^{R}(x), & c \le x \le d \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where $\mu_{\tilde{A}}^{L}(x) : [a, b] \to [0, 1]$ and $\mu_{\tilde{A}}^{R}(x) : [c, d] \to [0, 1]$. If both $\mu_{\tilde{A}}^{L}(x)$ and $\mu_{\tilde{A}}^{R}(x)$ are linear, then the fuzzy number $\tilde{A}$ is a trapezoidal fuzzy number and can be denoted by $\tilde{A} = (a,b,c,d)$. In a special case when $b = c$, the trapezoidal fuzzy numbers are transformed into triangular fuzzy numbers.

Some properties usually used to describe fuzzy numbers are support, core, height, left and right membership functions as graphically shown in Fig. 2 and mathematically defined in (5–9) respectively (Celikyilmaz and Turksen, 2009).

$$\mathrm{Supp}\left(\tilde{A}\right) = \left\{x \in X \middle| \mu_{\tilde{A}}(x) > 0\right\} \quad (5)$$

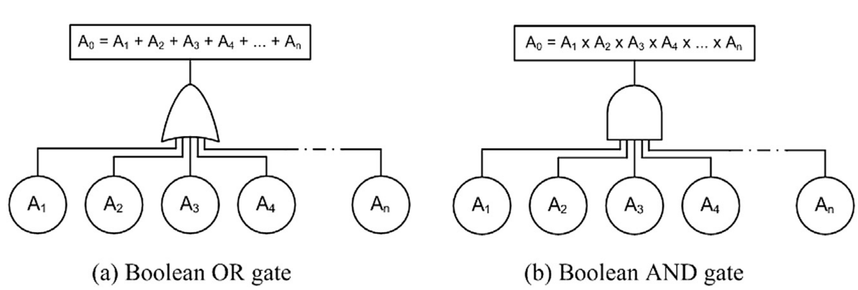

Fig. 1. Fault tree representations.