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A new failure mode and effects analysis model using Dempster–Shafer evidence theory and grey relational projection method

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ABSTRACT

Failure mode and effects analysis (FMEA) is an important analytical tool in reliability engineering to identify the critical potential failure modes. In this paper, a new FMEA model using Dempster–Shafer evidence theory (DSET) and grey relational projection method (GRPM) is proposed, which mainly manages two critical issues of FMEA: the presentation and handling of various types of uncertainty and the ranking of risk priorities of failure modes. DSET has a good advantage to express and model the assessment results of risk factors. GRPM is used to determine the risk priority order of the identified failure modes, where the double reference points (the positive/negative ideal alternative) are applied. Two illustrative cases are provided to demonstrate the effectiveness and practicality of the proposed method.

1. Introduction

Failure mode and effects analysis (FMEA) is an important analytical tool in reliability engineering (Mentes and Ozen, 2015; Liu et al., 2013a; Silveira et al., 2010; Zhang et al., 2010). It is used for defining, identifying and eliminating known or potential failures, errors and so on from the system, design, process or services before they occur (Liu et al., 2013b). The results of FMEA can not only increase compensating provisions, help designers employ the recommended action to reduce the likelihood of failures, but also can decrease the probability of failures rates and avoid hazardous accidents. FMEA has already been widely used in a broad range of industries, such as medical domain Kahraman et al. (2013); Mei et al. (2014), asset maintenance (Braaksma et al., 2013; Liu and Tsai, 2012; Bordelon, 1991), engineering design process (Kandukuri et al., 2016; Aouaouda et al., 2014; Kurt and Ozilgen, 2013; Wei et al., 2018) and others (Chen, 2013; Kandukuri et al., 2017).

FMEA can identify each failure mode and rank the risk of identified failure modes in order of importance using evaluation information of risk factors by FMEA team members. However, during the evaluation process, considering limited knowledge and different expertise or other reasons, various uncertainties are presented in team members' subjective assessments, such as imprecision, fuzziness, incompleteness. Thus it is a key point in FMEA to represent and handle various types of uncertainty when evaluating failure modes with respect to risk factors. Uncertainty is mainly caused by randomness and fuzziness. In general, the randomness is quantified by probability and the fuzziness is managed with fuzzy theory. Correspondingly, there are two main ways to express uncertainty: one is the probability in the form of definite numbers, the other is fuzzy language in the form of linguistic terms. Up to now, many uncertainty representation theories, including Dempster–Shafer evidence theory (DSET) (Dempster, 1967; Shafer et al., 1976), Z numbers (Cassanelli et al., 2006; Chen, 2013; Feng et al., 2006; Kandukuri et al., 2017) as well as D numbers (Mo and Deng, 2018), have been applied to FMEA. For example, Liu et al. (2014) and Bian et al. (2018) used D numbers to represent experts' assessments. In Liu et al. (2014), Liu et al. treated the uncertain assessments given by FMEA team members as linguistic terms expressed in intuitionistic fuzzy numbers (IFNs). Yang et al. (2011) applied DSET to FMEA to deal with different evaluation information of multiple experts.

From the perspective of uncertainty, we can divide FMEA issues into two types: probability FMEA and fuzzy FMEA. For probability FMEA, the uncertain assessment is expressed with probability. For fuzzy FMEA, when judgement is expressed with vague concepts such as low, medium and high, using fuzzy theory is essential when dealing with such situation. Fuzzy theory, which is an efficient method to model vague information (Sun et al., 2015; Wei et al., 2017; Han and Deng, 2018; Wang et al., 2018), like intuitionistic fuzzy sets can relate linguistic terms to appropriate membership functions to provide a better and more accurate analysis for the scores of failure modes (Tooranloo and sadat Ayatollah, 2016; Foroozesh et al., 2017).

For probability FMEA, D numbers has desirable properties in expressing uncertain information (Deng and Deng, 2018). However,

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several inherent shortcomings exist in D numbers because of the dissatisfaction of the associative property in combination operation and the complex operation. Dempster–Shafer evidence theory (DSET) is a powerful mathematical tool to reason with uncertain information, where basic probability assignment (BPA) and the combination rule are introduced to present various uncertainties and fuse multiple evidence from independent sources respectively (Xu and Deng, 2018; Zheng and Deng, 2018). In addition, as an extension of the grey relational theory, grey relational projection method (GRPM) is an effective method analysing the relationship between sequences with grey information. Nevertheless, to make the ranking results more accurate and reasonable in assessing the risk of failure modes, it is necessary to employ the double reference points (the positive ideal alternative and negative ideal alternative) in FMEA method. Based on two points above, in this paper, a new FMEA model based on Dempster–Shafer evidence theory and grey relational projection method is proposed. Moreover, the proposed method can also deal with fuzzy FMEA, the credit is attributed to the fact that intuitionistic fuzzy values can be handled in the framework of Dempster–Shafer evidence theory (Dymova and Sevastjanov, 2010, 2012). Two applications will be demonstrated to show the model's capacity to capture handling of various types of uncertainties.

The organization of the rest paper is as follows. Section 2 starts with a brief presentation of necessary related concepts. The proposed FMEA model based on DSET and GRPM is presented in Section 3. Section 4 investigates two applications to illustrate our proposed method. Discussion and conclusion are presented in Section 5.

2. Preliminaries

2.1. Dempster–Shafer evidence theory (DSET)

Dempster–Shafer evidence theory (DSET) is used for dealing with uncertain information (Li and Deng, 2018; Deng and Jiang, 2018b; Deng et al., 2018), decision making (Han and Deng, 2018; Chen and Deng, 2018) and network analysis (Deng and Jiang, 2018a; Bian and Deng, 2018; Li et al., 2018). In DSET, a fixed set of N mutually exclusive and exhaustive elements is defined, called the frame of discernment, and symbolized by $\Theta = \{H_1, H_2, H_3, \dots H_N\}$. $P(\Theta)$ is denoted as the power set composed of 2^N elements of Θ, each element of 2^N represents a proposition.

Definition 1. A basic probability assignment (BPA) is a function from $P(\Theta)$ to [0,1] defined by

$$m : P(\Theta) \to [0,1], A \mapsto m(A) \tag{1}$$

satisfying the following condition:

$$\sum_{A\in P(\Theta)} m(A) = 1, m(\emptyset) = 0 \tag{2}$$

BPA has an advantage of directly expressing the uncertainty by assigning the basic probability number to a subset composed of multiple elements, rather than to a single element.

Definition 2. Assume there are two bodies of evidence m_1 and m_2 respectively, m_1 and m_2 can be combined with Dempster's combination rule (Denœux, 2008) as follows:

$$m_1 \oplus m_2 = m(A) = \frac{\sum_{B\bigcap C=A} m_1(B)m_2(C)}{1-K} \tag{3}$$

where

$$K = \sum_{B\bigcap C=\emptyset} m_1(B)m_2(C) \tag{4}$$

K is called the conflict coefficient of two BPAs. Note that Dempster's combination rule meets associative property in combination operation. It strongly implies the agreement between multiple sources and ignores the conflict between them. However, when evidence highly conflicts with each other, the classic Dempster's rule of combination is not efficient (Zadeh, 1986; Zhang and Deng, 2018). To overcome this limitation, a discounting rule has been introduced in Dempster's combination rule given as below, which has superiority in handling conflict information and enhancing credibility.

Definition 3. Given a BPA m(A) and α be a discounting coefficient which represents the confidence (or reliability) degree one has in relative information source, then the discounted BPA m′(A) is defined as (Lefevre et al., 2002):

$$\begin{cases} m'(A) = \alpha \cdot m(A), A \neq \Theta, \\ m'(\Theta) = \alpha \cdot m(\Theta) + 1 - \alpha \end{cases} \tag{5}$$

2.2. The pignistic probability function $BetP_m$

Definition 4. Let m be a BPA on Θ. Its associated pignistic probability function $BetP_m$ (Liu, 2006): $\Theta \longrightarrow [0,1]$ is defined as follows:

$$BetP_m(B) = \sum_{A\subseteq\Theta, B\in A} \frac{1}{|A|}\frac{m(A)}{1-m(\emptyset)} \quad m(\emptyset) \neq 1, \tag{6}$$

where $|A|$ is the cardinality of subset A, m(∅) = 0. The main aim of $BetP_m$ is to translate a BPA into probability in order to make a decision.

2.3. Risk priority number (RPN)

The risk priority number (RPN) is applied in the traditional FMEA for the purpose of ranking the risk of potential failure modes. the higher RPN is, the more important the corresponding failure mode is. The RPN is a mathematic product of risk factors (occurrence (O), severity (S) and detection (D)) of a failure mode as below:

$$RPN = O \times S \times D \tag{7}$$

As shown in Eq. (7), three risk factors are considered: O and S are the frequency and seriousness (effect) of the failure, and D is the probability of the failure being detected before it reaches the customer. In general, each factor is evaluated by criticality analysis using a numeric scale (rating) from 1 to 10, detailed tables can be seen in Liu et al. (2014).

Nevertheless, the crisp RPN method shows some critical weaknesses when FMEA is applied in the real-world cases. The most important ones can be listed: (1) The relative weight of three risk factors is not taken into consideration. (2) Different combinations of O, S and D may produce exactly the same value of RPN, but their potential risk implications may be different. (3) Three risk factors are difficult to be precisely evaluated because of various types of uncertainty existing in experts' subjective assessment.

2.4. Grey relational projection method (GRPM)

Based on grey relational analysis (GRA) and vector projection, Grey relational projection method (GRPM) is developed (Feng and Xiao-hui, 2002). GRA method (Li and Tsai, 2009) is a useful tool to determine the difference in contribution between a reference series and each compared series. The compared series are alternative vectors deriving from sets based on attribute characteristics. The projection value is expressed based on the product of the norm and the cosine of the angle between the decision alternative and the ideal alternative (Zheng et al., 2010). The most obvious advantage of GRPM is that the result is based on original data, which confirms the reliability of the conclusion.

It is noteworthy that most applications of GRPM are established on single point (the ideal alternative), while effort in analysing building envelope evaluation by GRPM is lacking. In our paper, a double base point (the positive ideal alternative and negative ideal alternative) grey relational method in building envelope evaluation is applied (Liu et al., 2014). It simultaneously considers the projections on both the positive ideal alternative and negative ideal alternative, and a preference order is given according to their relative projection.

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