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Failure mode and effects analysis using D numbers and grey relational projection method

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ABSTRACT

Failure mode and effects analysis (FMEA) is a widely used risk assessment tool for defining, identifying and eliminating potential failures or problems in products, process, designs and services. Two critical issues of FMEA are the representation and handling of various types of assessments and the determination of risk priorities of failure modes. Many different approaches have been suggested to enhance the performance of traditional FMEA; however, deficiencies exist in these approaches. In this paper, based on a more effective representation of uncertain information, called D numbers, and an improved grey relational analysis method, grey relational projection (GRP), a new risk priority model is proposed for the risk evaluation in FMEA. In the proposed model, the assessment results of risk factors given by FMEA team members are expressed and modeled by D numbers. The GRP method is used to determine the risk priority order of the failure modes that have been identified. Finally, an illustrative case is provided to demonstrate the effectiveness and practicality of the proposed model.

1. Introduction

Failure mode and effects analysis (FMEA) is a widely used engineering technique for identifying and prioritizing potential failure modes in systems, designs, processes and/or services before they occur, with the intent to eliminate them or minimize the risk associated with them. When it is used for a criticality analysis, it is also referred to as failure mode, effects and criticality analysis (FMECA). FMEA was first developed as a formal design methodology in the 1960s by the aerospace industry with their obvious reliability and safety requirements (Bowles & Peláez, 1995). It can be employed to improve the safety and reliability of a system by identifying the critical potential failure modes and taking necessary preventive (or corrective) actions in the redesign stage of the system. The major concern of FMEA is to emphasize the prevention of problems linked to the proactive treatment of the system (Stamatis, 2003), rather than finding a solution after the failure happens (Geum, Cho, & Park, 2011). Due to its visibility and simplicity, FMEA is probably one of the most popular safety and reliability analysis tools for products and processes (Braglia, Frosolini, & Montanari, 2003a; Yang, Bonsall, & Wang, 2008), which has been widely used in a number of industries as a solution to various reliability problems (Feili, Akar, Lotfizadeh, Bairampour, & Nasiri, 2013; Jong, Tay, & Lim, 2013; Kahraman, Kaya, & Şenvar, 2013; Kurt & Ozilgen, 2013; Lin, Wang, Lin, & Liu, 2014).

Despite of its wide range of applications, FMEA still reveals some important weaknesses, especially when criticality analysis is conducted using risk priority numbers (RPNs). To overcome the shortcomings of the traditional FMEA, many new risk evaluation methods have been developed in the literature, such as technique for ordering preference by similarity to ideal solution (TOPSIS) (Braglia, Frosolini, & Montanari, 2003b; Song, Ming, Wu, & Zhu, 2013), analytic hierarchy process (AHP) (Braglia, 2000), VIKOR (VIsekriterijumska optimizacija i KOmpromisno Resenje) (Liu, Liu, Liu, & Mao, 2012), data envelopment analysis (DEA) (Chin, Wang, Poon, & Yang, 2009a; Garcia, Schirru, & Frutuoso Emelo, 2005), decision making trial and evaluation laboratory (DEMATEL) (Seyed-Hosseini, Safaei, & Asgharpour, 2006), hybrid approaches (Kutlu & Ekmekçioğlu, 2012; Liu et al., 2011; Pillay & Wang, 2003; Zhang & Chu, 2011) and so forth. In addition, Bowles and Peláez (1995) initially developed a fuzzy logic-based approach for prioritizing failures in a system FMECA, which uses fuzzy if-then rules extracted from expert knowledge and expertise to describe the relationships between *O*, *S*, *D* and the risk of failures. The fuzzy inference method provides a classical and generic risk evaluation framework to FMEA, and as a result it has been widely

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applied to different kinds of FMEA problems (Chin, Chan, & Yang, 2008; Gargama & Chaturvedi, 2011; Guimarães, Lapa, & Moreira, 2011; Jong et al., 2013; Kahraman et al., 2013; Tay & Lim, 2006; Vinodh, Aravindraj, Narayanan, & Yogeshwaran, 2012). Liu, Liu, and Li (2013) treated the uncertain assessments given by FMEA team members as linguistic terms expressed in intuitionistic fuzzy numbers (IFNs), and the intuitionistic fuzzy hybrid weighted Euclidean distance (IFHWED) operator has been used to rank the risk of failures in FMEA. Yang, Huang, He, Zhu, and Wen (2011) have applied the Dempster–Shafer (D–S) theory of evidence to FMEA to deal with different evaluation information of multiple experts, which may be inconsistent, imprecise and uncertain. Moreover, the mean value of RPN (PVRPN) has been used to determine the risk priority order of multiple failure modes.

In real-life applications, the risk factors like occurrence (*O*), severity (*S*) and detection (*D*) are difficult to be determined precisely. Also, FMEA is a group decision behavior and cannot be performed on an individual basis (Chin, Wang, Poon, & Yang, 2009b; Liu et al., 2011). Considering their different expertise and backgrounds, various uncertainties are present in FMEA team members' subjective and qualitative assessments, such as imprecision, fuzziness, incompleteness and so on. Therefore, one key issue of FMEA is the representation and handling of various types of uncertainties in evaluating failure modes with respect to the risk factors. Up to now, many uncertainty representation theories have been applied to FMEA, which include fuzzy set (Zadeh, 1965), intuitionistic fuzzy set (Atanassov, 1986), as well as D–S theory of evidence (Dempster, 1967; Shafer, 1976). Among them, D–S theory of evidence, also called D–S theory or evidence theory, has some desirable properties in expressing the uncertain information and combining multiple evidences from independent sources. Even so, several inherent shortcomings exist in the D–S theory because of its strong hypotheses and constraints on the frame of discernment and basic probability assignment (BPA), which lead to limitations in practical application (Deng, 2012; Deng, Hu, Deng, & Mahadevan, 2014a). On the other hand, determining the risk priorities of failure modes using the conventional RPN method has been criticized to have many shortcomings. Grey relation theory is one of the most popular approaches employed to enhance the risk evaluation capability of FMEA (Chang, Liu, & Wei, 2001; Geum et al., 2011; Liu, Li, You, & Chen, in press; Liu et al., 2011; Pillay & Wang, 2003). As an extension of the grey relation theory, grey relational projection (GRP) theory is an effective means analyzing the relationship between sequences with grey information and has been applied in many fields (Fu et al., 2011; Zhang, Jin, & Liu, 2013; Zheng, Jing, Huang, & Gao, 2010). However, effort in assessing the risk of failure modes by the GRP method is lacking. Moreover, the grey relation analysis methods used in FMEA are based on a single reference point (the ideal alternative). Thus, it is necessary to propose an improved FMEA model by employing the double reference points (the positive ideal alternative and negative ideal alternative) GRP method.

The background introduced above shows that it may be inappropriate to use the D–S theory for representing various evaluation information of multiple experts due to the limitations of the frame of discernment and BPA. Additionally, the grey relational analysis method cannot express the position relationship in the data curve between each alternative and the ideal solution or negative ideal solution although it is applicable for prioritization of failure modes in FMEA. Therefore, in this paper, a new representation of uncertain information, called D numbers (Deng, 2012; Deng, Hu, Deng, & Mahadevan, 2014b), is introduced to handle various assessments of risk factors provided by FMEA team members. An improved grey relational analysis method, i.e. GRP, is used to determine the risk priority order of the failure modes that have been identified. Based on the D numbers and the GRP method, a new risk priority model is then proposed for the risk evaluation in FMEA. The new model can not only effectively deal with the various uncertainties in the risk assessment process but also rank the risk of the identified failure modes in a comprehensive way. What is more important, the proposed model overcomes the deficiencies of the conventional RPN method and provides a new framework for prioritizing failure modes in FMEA. Finally, a case study of rotor blades for an aircraft turbine is provided to demonstrate the effectiveness and practicality of the proposed FMEA.

The rest of this paper is organized as follows. Section 2 gives a brief review about the traditional FMEA and its main shortcomings. The basic concepts of D numbers are presented in Section 3. In Section 4, the risk priority model for FMEA based on D numbers and GRP method is developed. An illustrative example is given in Section 5 to show the effectiveness of the proposed model and finally, some conclusions and future research directions are provided in Section 6.

2. FMEA

2.1. The traditional FMEA

FMEA is an analysis technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from the system, design, process, and/or service before they reach the customers (Stamatis, 2003). It can help risk analysts identify each possible failure mode and determine the effect of each failure, help them rank the risk of the identified failure modes in order of importance and also help them take appropriate corrective actions to reduce the likelihood of failures, decrease the probability of failure rates and avoid hazardous accidents. Detail procedures for carrying out an FMEA and its various applications in the different industries have been documented in Stamatis (2003) and Pillay and Wang (2003).

For the purpose of ranking the risk of potential failure modes, the traditional FMEA uses the risk priority number (RPN) to determine the risk priorities of failure modes. The RPN is a mathematic product of the risk factors occurrence (*O*), severity (*S*) and detection (*D*) of a failure mode. That is

$$RPN = O \times S \times D, \tag{1}$$

where *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 of the three risk factors is evaluated by FMEA team members using a 1 to 10 numeric scale, as expressed in Tables 1–3 (Liu, Liu, & Liu, 2013; Yang, Huang, He, Zhu, & Wen, 2011; Wang, Chin, Poon, & Yang, 2009). The failure modes with higher RPNs are viewed to be more important and should be corrected with higher priorities than those with lower RPNs.

Table 1
Traditional FMEA scale for occurrence.

Rating	Probability of failure	Possible failure rate
10	Extremely high: Failure almost inevitable	$\geqslant 1/2$
9	Very high	1/3
8	Repeated failures	1/8
7	High	1/20
6	Moderately high	1/80
5	Moderate	1/400
4	Relatively low	1/2, 000
3	Low	1/15, 000
2	Remote	1/150, 000
1	Nearly impossible	$\leqslant 1/1, 500, 000$