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A novel approach for failure mode and effects analysis using combination weighting and fuzzy VIKOR method

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ABSTRACT

Failure mode and effects analysis (FMEA) is one of the most popular reliability analysis tools for identifying, assessing and eliminating potential failure modes in a wide range of industries. In general, failure modes in FMEA are evaluated and ranked through the risk priority number (RPN), which is obtained by the multiplication of crisp values of the risk factors, such as the occurrence (O), severity (S), and detection (D) of each failure mode. However, the conventional RPN method has been considerably criticized for various reasons. To deal with the uncertainty and vagueness from humans' subjective perception and experience in risk evaluation process, this paper presents a novel approach for FMEA based on combination weighting and fuzzy VIKOR method. Integration of fuzzy analytic hierarchy process (AHP) and entropy method is applied for risk factor weighting in this proposed approach. The risk priorities of the identified failure modes are obtained through next steps based on fuzzy VIKOR method. To demonstrate its potential applications, the new fuzzy FMEA is used for analyzing the risk of general anesthesia process. Finally, a sensitivity analysis is carried out to verify the robustness of the risk ranking and a comparison analysis is conducted to show the advantages of the proposed FMEA approach.

1. Introduction

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Failure mode and effects analysis (FMEA) is a widely used engineering technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from system, design, process, and/or service before they reach the customer [1]. FMEA, intended to provide information for making risk management decisions, was first proposed by NASA in 1960s for their obvious reliability requirements. When it is used for a criticality analysis, it is also referred to as failure mode, effects and criticality analysis (FMECA). FMEA requires a cross-functional team which is built by experts from different departments (e.g., design, production, and quality) to systematically examine and quantify the relationships between failure modes, effects, causes, current controls, and recommended actions. Different from other risk assessment tools, the major concern of FMEA is to emphasize the prevention of problems linked to the proactive treatment of the system, rather than finding a solution after the failure happens. This can help decision makers adjust the existing programs, increase compensating provisions, employ the corrective actions to reduce the likelihood of failures, decrease the probability of failure rates and avoid hazardous accidents. As of now, FMEA has been widely used as a critical safety and reliability analysis tool in various industries, especially in the aerospace, automotive, nuclear, and healthcare industries [2–5].

Generally, criticality or risk assessment in FMEA is implemented by calculating the risk priority number (RPN) of each failure mode, which is obtained by multiplying the scores of risk factors like occurrence (O), severity (S), and detection (D). However, in many real-life cases, the conventional RPN method shows some important weaknesses regarding the rationality of the approach. Therefore, a wide variety of methods have been proposed in the literature to overcome the shortcomings and improve the effectiveness of the traditional FMEA. Among these methods we can mention artificial intelligence techniques such as fuzzy rule-base system [6–9], adaptive resonance theory [10], and cognitive map [11]; mathematical programming methods such as data envelopment analysis (DEA) [12] and linear programming [13]; multi-criteria decision making (MCDM) methods such as technique for order preference by similarity to ideal solution (TOPSIS) [14,15], decision-making trial and evaluation laboratory (DEMATEL) [16,17], and gray relational analysis (GRA) [18,19]; integrated approaches such as

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similarity measure and adaptive resonance theory [20], D numbers and gray relational projection method [21], fuzzy analytic hierarchy process (AHP) and fuzzy TOPSIS [5], and other methods and techniques [22–24]. Furthermore, it is usually difficult and inaccurate to give a "direct" and correct numerical evaluation of the three risk factors and much information in FMEA can be expressed in linguistic terms such as *likely*, *important* or *very high* and so on [25,26]. Fuzzy set theory [27] is the tool for transforming the vagueness of human perception and recognition and its decision making ability into a mathematical formula. It provides meaningful representation of measurement for uncertainties and vague concepts expressed in natural language. In comparison with strictly numerical models, the approaches based on fuzzy logic provide the following benefits [7,8,28,29], and the most important ones are stated below: First, both quantitative data and qualitative information can be used and managed in a consistent manner during the FMEA analysis. Second, the risk of failure modes can be assessed directly using the linguistic variables that are employed in making the criticality assessment. Finally, fuzzy logic allows vague data to be used, so it enables the treatment of many states of components and system and other fuzzy information included in FMEA.

On the other side, VIKOR (VIsekriterijumska optimizacija i KOmpromisno Resenje) method was first developed by Opricovic and Tzeng [30] to solve MCDM problems with conflicting and noncommensurable (different units) criteria, assuming that compromising is acceptable for conflict resolution, the decision maker wants a solution that is the closest to the ideal, and the alternatives are evaluated according to all established criteria. This method focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria, and on proposing compromise solution(s) [31]. Due to its characteristics and capabilities, the VIKOR method has been considerably employed by researchers to resolve many practical decision making problems. For example, Liu et al. [32] used a hybrid MCDM model combining DEMATEL-based analytic network process (DANP) and modified VIKOR for solving the material selection problems of multiple dimensions and criteria that are interdependent. Hu, Lu and Tzeng [33] utilized a MCDM model combining DEMATEL with ANP and VIKOR methods to handle the complex interrelated relationships among dimensions and criteria and find the best way to explore smart phone improvements and Hsu et al. [34] used a hybrid MCDM model integrating DANP with VIKOR to select the best vendor for conducting the recycled material. Rezaie et al. [35] applied a combined fuzzy AHP and VIKOR method to evaluate the performance of the cement firms in Iran and Pourebrahim et al. [36] used an integrated VIKOR-fuzzy AHP method to make a selection among criteria and alternatives for conservation development in coastal areas. Yalcin et al. [37] utilized an evaluation approach using both fuzzy AHP and VIKOR methods to rank the companies of each sector in the Turkish manufacturing industry. On the other hand, some researchers have employed VIKOR method under fuzzy environment. For instance, Mehbodniya et al. [38] used a fuzzy extension of VIKOR for target network selection in heterogeneous wireless environments and Liu et al. [39] utilized an extended VIKOR method for site selection in municipal solid waste management under fuzzy environment. Tadić, Zečević and Krstić [40] developed a novel hybrid MCDM model that combines fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR for city logistics concept selection. Dincer and Hacioglu [41] evaluated the performance of the banks in Turkey based on the customer satisfaction competencies applying fuzzy VIKOR and AHP methods. Vinodh et al. [42] dealt with the concept design selection in fit environment using fuzzy VIKOR method so as to satisfy the customers' dynamic requirements.

In this paper, the fuzzy VIKOR method is extended to find a compromise priority ranking of failure modes according to the risk factors in FMEA. To deal with the uncertainty and vagueness in risk evaluation process, linguistic variables, expressed in triangular fuzzy number, are used to assess the fuzzy relative importance among risk factors and the fuzzy ratings of failure modes. Combination of fuzzy AHP and entropy method is applied for risk factor weighting. The extended fuzzy VIKOR method is used to rank failure modes in term of their overall risk on risk factors. As a result, a risk evaluation methodology by using combination weighting and fuzzy VIKOR method is presented to deal with the risk evaluation problems in FMEA. To validate the application of the model and to examine its effectiveness, the proposed methodology is used for analyzing the risk of general anesthesia process in a university hospital.

The rest of the paper is organized as follows. The traditional FMEA and its shortcomings are presented briefly in Section 2. The fuzzy set theory, fuzzy AHP method, Shannon Entropy and fuzzy VIKOR method are introduced in Section 3. Section 4 is about the proposed risk evaluation methodology for FMEA. A numerical example of general anesthesia process is offered in Section 5 and some conclusions are made in Section 6.

2. FMEA

2.1. The traditional FMEA

FMEA is an important technique used to identify and eliminate known or potential failures to enhance the reliability and safety of complex systems. For analyzing a specific product or system, a cross-functional expert team should be set up to conduct FMEA first. The first step in FMEA is to identify all possible failure modes of the product or system. Next, critical analysis is performed on the identified failure modes taking into consideration the risk factors: occurrence (O), severity (S), and detection (D).

Conventionally, the ranking of failure modes for corrective actions is determined in terms of the risk priority number (RPN), which is the mathematical product of the O, S, and D corresponding to the failure modes. That is

$$RPN = O \times S \times D, \quad (1)$$

where O is the probability of the failure, S is the severity of the failure, and D is the probability of not detecting the failure. In order to obtain the RPN of a potential failure mode, the traditional FMEA uses an integer scale from 1 to 10 for evaluating the three risk factors. Generally, the failure modes with higher RPNs are considered to be more important and will be given higher priorities for correction. According to the values of RPNs, the failure modes can be prioritized and then proper remedial actions should be preferentially taken on the failure modes with high levels of risk.

2.2. Shortcomings of FMEA

The traditional FMEA is a systematic, efficient and effective method, capable of improving the safety and reliability of systems; however, the conational RPN method has been criticized as having many limitations and problems [6,7,13,17,28,43,44], some of which are given as follows:

- The relative weights of risk factors are not taken into account. The risk factors O, S, and D are given to have the equal importance, which may not be the case in many practical applications of FMEA.
- Different sets of O, S, and D scores may produce exactly the identical value of RPN, but their hidden risk implications may be completely different. This may cause a waste of resources and time, or in some cases, some high-risk failure modes being ignored.
- The mathematical formula for computing RPN is questionable and strongly sensitive to variations in risk factor assessments.

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