Risk evaluation approaches in failure mode and effects analysis: A literature review

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Abstract

Failure mode and effects analysis (FMEA) is a risk assessment tool that mitigates potential failures in systems, processes, designs or services and has been used in a wide range of industries. The conventional risk priority number (RPN) method has been criticized to have many deficiencies and various risk priority models have been proposed in the literature to enhance the performance of FMEA. However, there has been no literature review on this topic. In this study, we reviewed 75 FMEA papers published between 1992 and 2012 in the international journals and categorized them according to the approaches used to overcome the limitations of the conventional RPN method. The intention of this review is to address the following three questions: (i) Which shortcomings attract the most attention? (ii) Which approaches are the most popular? (iii) Is there any inadequacy of the approaches? The answers to these questions will give an indication of current trends in research and the best direction for future research in order to further address the known deficiencies associated with the traditional FMEA.

Keywords:
Failure mode and effects analysis
Risk evaluation
Risk priority number

1. Introduction

Traditionally, criticality or risk assessment in FMEA is carried out by developing a risk priority number (RPN). Nevertheless, the crisp RPN method shows some important weaknesses when FMEA is applied in the real-world cases. Therefore, many alternative approaches have been suggested in the literature to resolve some of the shortcomings of the traditional RPN method and to implement FMEA into real world situations more efficiently. To the best of our knowledge, no research has been done on the review of approaches employed to enhance the performance of FMEA. This paper provides a review of those academic works attempting to deal with problems in the traditional RPN method and classify the existing literature by the approaches used. Related articles appearing in the international journals from 1992 to 2012 are gathered and analyzed. Based on the 75 journal articles collected, the specific objectives of this review are:

- To look at shortcomings surrounding the traditional methodology and identify which issues attract the most attention in FMEA literature?
- To describe the approaches used in FMEA literature and find which approaches were prevalently applied?
- To evaluate the approaches used in FMEA literature and check is there any inadequacy of the approaches?

This review not only provides evidence that some alternate approaches are better than the traditional RPN approach, but also aids the researchers and risk analysts in applying the FMEA effectively. Some recent trends and future research directions are also highlighted based on the review.
The rest of the paper is organized as follows. The traditional FMEA and its major shortcomings are provided in Section 2. In Section 3 we explain the framework used for classifying FMEA literature and present the results of literature review. Section 4 analyses the most prevalently used approaches, finds out the limitations of the approaches and discusses the weighting methods for risk factors. Finally, we will draw conclusions and make suggestions for future research in Section 5.

2. FMEA

2.1. The traditional FMEA

FMEA is an important technique that is used to identify and eliminate known or potential failures to enhance the reliability and safety of complex systems and is intended to provide information for making risk management decisions. In order to analyze a specific product or system, a cross-functional team should be established for carrying out FMEA first. The first step in FMEA is to identify all possible potential failure modes of the product or system by a session of systematic brainstorming. After that, critical analysis is performed on these failure modes taking into account the risk factors: occurrence (O), severity (S) and detection (D). The purpose of FMEA is to prioritize the failure modes of the product or system in order to assign the limited resources to the most serious risk items.

In general, the prioritization of failure modes for corrective actions is determined through the risk priority number (RPN), which is obtained by finding the multiplication of the O, S and D of a failure. That is

\[ RPN = O \times S \times D. \]

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. For obtaining the RPN of a potential failure mode, the three risk factors are evaluated using the 10-point scale described in Tables 1–3. The higher the RPN of a failure mode, the greater the risk is for product/system reliability. With respect to the scores of RPNs, the failure modes can be ranked and then proper actions will be preferentially taken on the high-risk failure modes. RPNs should be recalcualted after the corrections to see whether the risks have gone down, and to check the efficiency of the corrective action for each failure mode.

2.2. Shortcomings of FMEA

The traditional FMEA has been proven to be one of the most important early preventative actions in system, design, process or service which will prevent failures and errors from occurring and reaching the customer. However, the conventional RPN method has been criticized extensively in the literature for a variety of reasons. All the shortcomings reported in the FMEA literature are summarized in Appendix 2 and the most important ones could be found in Table 4.

3. Review of the existing literature

In this section, we present the results of an extensive literature search on risk evaluation in FMEA for priority ranking of failure modes. The source used for our study was academic journal articles published between 1992 and 2012. Publications in languages other than English and non-refereed professional publications, such as textbooks, doctoral dissertations and conference proceedings, were not included. Furthermore, we only included articles that report on a method or technique that specifically aims at overcoming some of the drawbacks of the traditional FMEA. This implies that articles merely describing the FMEA process or applying the traditional FMEA have not been included. Also, articles reporting on methods for automating FMEA implementation were excluded. (For the interested reader, a review of the articles related to this topic is given in Appendix 2.)

Vast majority of risk priority models are found in the literature to improve the criticality analysis process of FMEA. Therefore we propose a framework for classifying the reviewed papers depending upon the failure mode prioritization methods that have been identified. In this review, we divide the methods used in the literature into five main categories, which are multi-criteria decision making (MCDM), mathematical programming (MP), artificial intelligence (AI), hybrid approaches and others. The five categories, each with their own related approaches and references, are reported in Table 5. It should be noted that some references, like Gargama and Chaturvedi (2011) and Pillay and Wang (2003), include more than one method to solve the traditional FMEA problems. In this case it can be classified in more than one category in the table. Hence, the sum of the figures for the five categories (80 items) does not match the total number of reviewed papers (75 items). In what follows, we more specifically go into the references and show what has been done.

3.1. MCDM approaches

Franceschini and Galetto (2001) presented a multi-expert MCDM (ME-MCDM) technique for carrying out the calculation of the risk priority of failures in FMEA, which is able to deal with the information provided by the design team, normally given on qualitative scales, without necessitating an arbitrary and artificial numerical conversion. In their method, risk factors were interpreted as evaluation criteria, while failure modes as the alternatives to be selected. The method considered each decision-making criterion as a fuzzy subset over the set of alternatives to be selected. After the aggregation of evaluations expressed on each criterion for a given alternative, the failure mode were determined using the group-based ER approach, which includes assessing risk factors using belief structures, synthesizing individual belief structures into group belief structures, aggregating the group belief structures into overall belief structures, converting the overall belief structures into expected risk scores, and ranking the expected
risk scores using the minimax regret approach (MRA). Yang, Huang, He, Zhu, and Wen (2011) also adopted evidence theory to aggregate the risk evaluation information of multiple experts. However, all individual and interval assessment grades were assumed to be crisp and independent of each other in the proposed model. It did not considerate the occasion in FMEA where an assessment grade may represent a vague concept or standard and there may be no clear cut between the meanings of two adjacent grades.

Braglia (2000) developed a multi-attribute failure mode analysis (MAFMA) approach based on the analytic hierarchy process (AHP) technique, which views the risk factors (O, S, D and expected cost) as decision criteria, possible causes of failure as decision alternatives and the selection of cause of failure as decision goal. The goal, criteria and alternatives formed a three-level hierarchy, where the pair wise comparison matrix was used to estimate criterion weights and the local priorities of the causes in terms of the expected cost attribute. The conventional scores for O, S and D were normalized as the local priorities of the causes with respect to O, S and D, respectively, and the weight composition technique in the AHP was utilized to synthesize the local priorities into the global priority, based on which the possible causes of failure were ranked. Making reference to Braglia (2000), Carmignani (2009) presented a priority-cost FMECA (PC-FMECA), which allows for the calculation of a new RPN and the introduction of the concept of profitability taking into consideration the corrective action cost. The numerical tool was also presented in the paper.

Braglia, Frosolini, and Montanari (2003b) presented an alternative multi-attribute decision-making approach called fuzzy technique for order preference by similarity to ideal solution (TOPSIS) approach for FMECA, which considers the failure causes as the alternatives to be ranked, the risk factors O, S and D related to a failure mode as criteria. The failures were prioritized based on the measurement of the Euclidean distance of an alternative from an ideal goal. In the proposed fuzzy TOPSIS approach, the three risk factors and their corresponding weights of importance were allowed to be assessed using triangular fuzzy numbers rather than precise crisp numbers, giving a final ranking for failure causes that is easy to interpret.

Chang, Wei, and Lee (1999) used fuzzy method and grey theory for FMEA, where fuzzy linguistic variables were used to evaluate the risk factors O, S and D, and grey relational analysis was applied to determine the risk priority of potential causes. To carry out the grey relational analysis, fuzzy linguistic variables were defuzzified as crisp values, the lowest levels of the three risk factors were defined as a standard series, and the assessment information of the three risk factors for each potential cause was viewed as a comparative series, whose grey relational coefficient and degree of relational with the standard series were computed in terms of the grey theory. Stronger degree of relational means smaller effect of potential cause. Hence, the increasing order of the degrees of relational represents the risk priority of the potential problems to be
and Wang (2003) and Sharma and Sharma (in press) also be found in Sharma, Kumar, and Kumar (2008b, 2007d), Pillay and grey theory for prioritization of failure modes in FMEA can using the traditional scores 1–10 for the three risk factors rather than using the grey theory for FMEA, but the degrees of relational were computed by different authors. In Chang, Liu, and Wei (2001), they also utilized the grey relational analysis was applied with a two-phase structure: one for calculating the risk score of each dimension: O, S and D, and the other for calculating the final risk priority.

### Table 4
The major shortcomings of FMEA.

<table>
<thead>
<tr>
<th>Shortcomings</th>
<th>Literature</th>
<th>Total number</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPNs are not continuous with many holes</td>
<td>Liu et al. (2012), Chang and Cheng (2011, 2010), Chang et al. (2010), Chang (2009), Keskin and Zkan (2009), Carmignani (2009), Franceschini and Galetto (2001), Garcia et al. (2005), Chang and Sun (2009)</td>
<td>10</td>
</tr>
<tr>
<td>Interdependencies among various failure modes and effects are not taken into account</td>
<td>Xu et al. (2002), Chin et al. (2008), Braglia et al. (2007), von Ahsen (2008), Carmignani (2009), Nepal et al. (2008), Zammori and Gabbrielli (2011), Shahin (2004), Chang and Sun (2009), Gandhi and Agrawal (1992)</td>
<td>10</td>
</tr>
<tr>
<td>The RPN elements have many duplicate numbers</td>
<td>Gargama and Chaturvedi (2011), Chang and Cheng (2011, 2010), Chang et al. (2010), Chang (2009), Seyed-Hosseini et al. (2006), Sanák and Prabhu (2001), Garcia et al. (2005), Chang and Sun (2009)</td>
<td>9</td>
</tr>
<tr>
<td>The RPN considers only three risk factors mainly in terms of safety</td>
<td>Chin et al. (2009b), Liu et al. (2011), Yang et al. (2008), Braglia et al. (2003a, 2003b), Chang and Cheng (2010), Braglia (2000), Carmignani (2009), Zammori and Gabbrielli (2011)</td>
<td>9</td>
</tr>
</tbody>
</table>

improved. In Chang, Liu, and Wei (2001), they also utilized the grey theory for FMEA, but the degrees of relational were computed using the traditional scores 1–10 for the three risk factors rather than fuzzy linguistic variables. Similar applications of fuzzy method and grey theory for prioritization of failure modes in FMEA can also be found in Sharma, Kumar, and Kumar (2008b, 2007d), Pillay and Wang (2003) and Sharma and Sharma (in press).

Geum, Cho, and Park (2011) proposed a systematic approach for identifying and evaluating potential failures using a service-specific FMEA and grey relational analysis. Firstly, the service-specific FMEA was provided to reflect the service-specific characteristics, incorporating 3 dimensions and 19 sub-dimensions to represent the service characteristics. As the second step, under this framework of service-specific FMEA, the risk priority of each failure mode was calculated using grey relational analysis. In this paper, grey relational analysis was applied with a two-phase structure: one for calculating the risk score of each dimension: O, S and D, and the other for calculating the final risk priority.

Seyed-Hosseini, Safaei, and Asgharpour (2006) proposed a method called decision making trial and evaluation laboratory (DEMATEL) for reprioritization of failure modes in a system FMEA for corrective actions. In the proposed methodology, the failure information in FMEA was described as a weighted digraph, where nodes indicate the failure modes or causes of failures and directed connections (edges) indicate the effects failure modes on together. Also, the connection weights indicate the degree or severity of effects of one alternative on another. An indirect relationship was defined as a relationship that could only move in an indirect path between two alternatives and meant that a failure mode could be the cause of other failure mode(s). Alternatives having more effect to another were assumed to have higher priority and called dispatcher and those receiving more influence from another were assumed to have lower priority and called receiver. As a result, the prioritization of alternatives can be determined in terms of the type of relationships and severity of influences of them on another.
Chang, Cheng, and Chang (2010) proposed an approach, which utilizes the intuitionistic fuzzy set ranking technique, for reprioritization of failures in a system FMECA. The triangle intuitionistic fuzzy set for each unit fault was defined according to the experts’ experiences. Then the influential power of each unit for the system and increasable reliability for the whole system were calculated based on the vague fault tree analysis definition proposed by Chang, Chang, Liao, and Cheng (2006). The risk of failures was finally ranked according to the degree of influence of each unit fault.

Recently, Liu, Liu, Liu, and Mao (2012) applied the VIKOR method, which was developed for multi-criteria optimization for complex systems, to find the compromise priority ranking of failure modes according to the risk factors in FMEA. In the methodology, linguistic variables, expressed in trapezoidal or triangular fuzzy numbers, were used to assess the ratings and weights for the risk factors O, S and D. The extended VIKOR method was used to determine risk priorities of the failure modes that have been identified.

3.2. Mathematical programming approaches

Wang, Chin, Poon, and Yang (2009b) proposed fuzzy risk prioritization numbers (FRPNs) for prioritization of failure modes to deal with the problem that it is not be realistic in real applications to determine the risk priorities of failure modes using the RPNs because they require the risk factors of each failure mode to be precisely evaluated. In the paper, the FRPNs were defined as fuzzy weighted geometric means of the fuzzy ratings for O, S and D, and can be computed using \( n \)-level sets and linear programming models. Finally, the FRPNs were defuzzified using centroid defuzzification method for ranking purpose. In addition, Gargama and Chaturvedi (2011) employed a benchmark adjustment search algorithm, rather than the linear programming approach, to determine the weighted fuzzy geometrical means of \( n \) level sets to compute the FRPNs. In Chen and Ko (2009a, 2009b), the FRPNs was defined as fuzzy ordered weighted geometric averaging (FOWGa) (Xu & Da, 2003) of the three risk factors.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Approaches</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCDM (22.50%)</td>
<td>ME-MCDM</td>
<td>Franceschini and Galetto (2001)</td>
</tr>
<tr>
<td></td>
<td>Evidence theory</td>
<td>Chin et al. (2009b), Yang et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>AHP/ANP</td>
<td>Braglia (2000), Carmignani (2009), Hu et al. (2009), Zammori and Gabbrielli (2011)</td>
</tr>
<tr>
<td></td>
<td>Fuzzy TOPSIS</td>
<td>Braglia et al. (2003b)</td>
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<td></td>
<td>DEMATEL</td>
<td>Seyed-Hosseini et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Intuitionistic fuzzy set ranking technique</td>
<td>Chang et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>VIKOR</td>
<td>Liu et al. (2012)</td>
</tr>
<tr>
<td>Mathematical programming</td>
<td>Linear programming</td>
<td>Wang et al. (2009b), Gargama and Chaturvedi (2011), Chen and Ko (2009a, 2009b)</td>
</tr>
<tr>
<td>(8.75%)</td>
<td>DEA/Fuzzy DEA</td>
<td>Garcia et al. (2005), Chang and Sun (2009), Chin et al. (2009a)</td>
</tr>
<tr>
<td>Artificial intelligence</td>
<td>Rule-base system</td>
<td>Sankar and Prabhu (2001)</td>
</tr>
<tr>
<td>Integrated approaches</td>
<td>Fuzzy ART algorithm</td>
<td>Keskin and Zkan (2009)</td>
</tr>
<tr>
<td>(11.25%)</td>
<td>Fuzzy cognitive map</td>
<td>Peláez and Bowles (1996)</td>
</tr>
<tr>
<td></td>
<td>Fuzzy AHP-Fuzzy rule-base system</td>
<td>Abdelgawad and Fayek (2010)</td>
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<tr>
<td></td>
<td>WLSM-MOI-Partial ranking method</td>
<td>Zhang and Chu (2011)</td>
</tr>
<tr>
<td></td>
<td>OWGA operator-DEMATEL</td>
<td>Chang (2009)</td>
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<tr>
<td></td>
<td>IFS-DEMATEL</td>
<td>Chang and Cheng (2010)</td>
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<tr>
<td></td>
<td>Fuzzy OWA operator-DEMATEL</td>
<td>Chang and Cheng (2011)</td>
</tr>
<tr>
<td></td>
<td>2-tuple-OWA operator</td>
<td>Chang and Wen (2010)</td>
</tr>
<tr>
<td></td>
<td>FER-Grey theory</td>
<td>Liu et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Fuzzy AHP-fuzzy TOPSIS</td>
<td>Kurtlu and Ekmekcioğlu (2012)</td>
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<tr>
<td></td>
<td>ISM-ANP-UPN</td>
<td>Chen (2007)</td>
</tr>
<tr>
<td>(17.50%)</td>
<td>Monte Carlo simulation</td>
<td>Bevilacqua et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>Minimum cut sets theory (MCS)</td>
<td>Xiao et al. (2011)</td>
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<tr>
<td></td>
<td>Boolean representation method (BRM)</td>
<td>Wang et al. (1995)</td>
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<tr>
<td></td>
<td>Digraph and matrix approach</td>
<td>Gandhi and Agrawal (1992)</td>
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<td></td>
<td>Kano model</td>
<td>Shahin (2004)</td>
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<tr>
<td></td>
<td>Probability theory</td>
<td>Sant’Anna (2012)</td>
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</table>
Garcia, Schirru, and Frutuoso Emelo (2005) presented a fuzzy data envelopment analysis (DEA) approach for FMEA in which typical risk factors O, S, and D were modeled as fuzzy sets, and the fuzzy possibility DEA model introduced by Lertworasirikul, Fang, Joines, and Lw Nuttle (2003) was used for determining the ranking indices among failure modes. Chang and Sun (2009) also applied DEA to enhance the assessment capability of FMEA; however, the inputs (O, S, and D) of FMEA were crisp values (from 1 to 10) instead of fuzzy sets in their proposed model.

Chin, Wang, Poon, and Yang (2009a) argued that Garcia et al.'s (2005) approach is computationally very complicated and also could not produce a full ranking for the failure modes to be prioritized. Based on these arguments, they proposed a DEA-based FMEA which takes into account the relative importance weights of risk factors, but has no need to specify them subjectively. The weights were determined by DEA models and they differed from one failure mode to another. The proposed FMEA measured the maximum and minimum risks of each failure mode. The two risks were then geometrically averaged to reflect the overall risks of the failure modes, based on which the failure modes can be prioritized. Incomplete and imprecise information on the evaluation of risk factors was also considered in the FMEA.

3.3. Artificial intelligence approaches

3.3.1. Rule-base system

Sankar and Prabhu (2001) presented a modified approach for prioritization of failures in a system FMEA, which uses the ranks 1–1000, called risk priority ranks (RPRs), to represent the increasing prioritization of failures in a system FMEA, which uses the ranks 1–1000, called risk priority ranks (RPRs), to represent the increasing risk of the 1000 possible severity–occurrence–detection combinations. These 1000 possible combinations were tabulated by an expert in order of increasing risk and can be represented in the form of ‘if-then’ rules. The failures having a higher rank were given a higher priority than those having a lower rank.

3.3.2. Fuzzy rule-base system

Bowles and Peláez (1995) described a fuzzy logic-based approach for prioritizing failures in a system FMEA, which uses linguistic variables to describe O, S, and D and the riskiness of failure. The relationships between the riskiness and O, S, D were characterized by a fuzzy if-then rule base which was developed from expert knowledge and expertise. Crisp ratings for O, S, and D were fuzzified to match the premise of each possible if-then rule. All the rules that have any truth in their premises were fired to contribute to the fuzzy conclusion set. The fuzzy conclusion was then defuzzified by the weighted mean of maximum method (WMoM) as the ranking value of the risk priority. Moss and Woodhouse (1999) also suggested a similar fuzzy logic approach for criticality analysis. Based on the fuzzy logic approaches described above, Xu, Tang, Xie, Ho, and Zhu (2002) developed a fuzzy FMEA assessment expert system for diesel engine’s gas turbocharger, Zafiropoulos and Diallynas (2005) presented a fuzzy FMEA assessment system for a power electronic devices such as a switched mode power supply (SMPS), Chin, Chan, and Yang (2008) developed a fuzzy FMEA based product design system called EPDS-1, and Nepal, Yadav, Monplaisir, and Murat (2008) presented a general FMEA framework for capturing the failures due to system/component interactions at the product architecture (PA) level.

Puente, Pino, Priore, and de la Fuente (2002) presented a criticality assessment approach based on qualitative rules which provide a ranking of the risks of potential causes of failure. The methodology assigned a risk priority class to each cause of failure in an FMEA, depending on the importance given to the three risk factors (O, S, and D) related to a failure mode. The structure of the qualitative rules was of the if-then rule type and all the 125 rules in the FMEA were shown in the form of a three-dimensional graph. In order to optimize the risk-discrimination capabilities of the different causes of failure, a modified version of the technique integrating with fuzzy logic was also proposed by the authors.

Pillay and Wang (2003) proposed a fuzzy rule base approach that does not require a utility function to define the O, S, and D considered for the analysis. This was achieved by using information gathered from experts and integrating them in a formal way to reflect a subjective method of ranking risk. The proposed approach needs to set up the membership functions of the three risk factors O, S, and D first. Each of the failure modes was then assigned a linguistic variable representing the three risk factors. Using the fuzzy rule base generated, these three variables were integrated to produce linguistic variables representing the risk ranking of all the failure modes.

Yang, Bonsall, and Wang (2008) presented a fuzzy rule-based Bayesian reasoning (FuBar) approach for prioritizing failures in FMEA. The technique was specifically developed to deal with some of the drawbacks concerning the use of conventional fuzzy logic (i.e., rule-based) methods in FMEA. In their approach, subjective belief degrees were assigned to the consequent part of the rules to model the incompleteness encountered in establishing the knowledge base. A Bayesian reasoning mechanism was then used to aggregate all relevant rules for assessing and prioritizing potential failure modes.

Gargama and Chaturvedi (2011) proposed a fuzzy FMEA model for prioritizing failures modes based on the degree of match and fuzzy rule-base to overcome some limitations of traditional FMEA. The proposed model employed the belief structure for the assessment of risk factors, and then converted randomness in the assessed information into a convex normalized fuzzy number. The degree of match (DM) was used thereafter to estimate the matching between the assessed information and the fuzzy sets of risk factors. This computed DM then became the inputs to the fuzzy rule-based systems where rules were processed resulting in failure classification with degree of certainty.

The fuzzy RPN mode typically requires a large number of rules, and it is a time-consuming and tedious process in acquiring rules from domain experts in building a fuzzy if-then rule base. Therefore, Braglia and Bevilaqua (2000) proposed the use of AHP for obtaining the rules for a particular fuzzy criticality assessment model. Another characteristic of this model was the use of a triangular approach as ‘crisp’ inputs in fuzzy models to evaluate the different opinions of the maintenance staff. Braglia, Frosolini, and Montanari (2003a) proposed a risk function which permits fuzzy if-then rules to be generated in an automatic way. The risk function links the normalized RPN values obtained by every combination of the mode values of each membership function for each risk factor with the corresponding linguistic variable sets of final failure risk evaluation, where the normalized RPN were defined as RPN/1000. Tay and Lim (2006a) argued that not all the rules are actually required in the fuzzy RPN model and proposed a guided rules reduction system (GRRS) to provide guidelines to the users which rules are required and which can be eliminated. By employing the GRRS, the users do not need to provide all the rules, but only the important ones when constructing a fuzzy if-then rule base. In Tay and Lim (2010), the authors also used fuzzy rule interpolation and reduction techniques to design weighted fuzzy RPN models and demonstrated the ability of the weighted fuzzy RPN model in failure risk evaluation with a reduced rule base.

Rule reduction method has been applied by many other researchers to reduce the size of a fuzzy if-then rule base. In Pillay and Wang (2003), a total of 125 rules were generated when the proposed approach was applied to an ocean going fishing vessel. However, these rules were combined and the total number of rules in the fuzzy rule base was reduced to 35 rules. Sharma et al. (2005) employed 27 fuzzy if-then rules in their fuzzy FMEA for the feeding
system in a paper mill, and they reduced a total of 125 fuzzy if-then rules to 30 rules in the applications to other systems of the paper mill, such as pulping system, forming and press systems, washing system, paper machine and dryer system (Sharma, Kumar, & Kumar, 2007a, 2007b, 2007c, 2007d, 2008a, 2008b, 2008c; Sharma & Sharma, 2010, 2012). Similar rule reduction was also applied by Guimarães and Franklin Lapa (2004), Guimarães and Lapa (2004, 2006, 2007), and Guimarães, Lapa, and Moreira (2011) in their applications of fuzzy FMEA to an auxiliary feed-water system of a two-loop pressurized water reactor (PWR), a PWR chemical and volume control system (CVCs), a light-water reactors passive system of a independent loop boiling water reactor (BWR), a standard four-loop PWR containment cooling system (CCS), and a digital feed-water control system (DFWCS) of a two-loop PWR.

3.3.3. Fuzzy ART algorithm
Keskin and Özkan (2009) applied the fuzzy adaptive resonance theory (Fuzzy ART) neural networks to evaluate RPN in FMEA. In the study, occurrence, severity and detection values constituting RPN value were evaluated separately for each input. RPN values composed inputs and each input in its own was presented as O, S and D to the system. In each case, an input composed of three data (O, S and D) was presented to the system by efficient parameter results obtained from application of FMEA on test problems and similar inputs were clustered according to the three parameters. Finally, arithmetic mean of the input values in each obtained failure class was used for prioritization.

3.3.4. Fuzzy cognitive map
Peláez and Bowles (1996) applied fuzzy cognitive maps (FCMs) to model the behavior of a system for FMEA. The FCM was a diagram to represent the causality of failures with failure node and causal relation path. The path was described by using linguistic variables such as ‘some, always, often’ and relative scales were assigned for each term. Then min–max inference approach was used to evaluate the net causal effect on any given node and weighted mean of maximum method was used as defuzzification technique to extract the resulting confidence values on linguistic variables.

3.4. Integrated approaches
Zhang and Chu (2011) described a fuzzy-RPNs-based method for FMEA under uncertainty integrating weighted least square method (WLSM), the method of imprecision (MOI) and partial ranking method. In this study, multi-granularity linguistic term sets were adopted by decision makers in FMEA team for expressing their judgments; a fuzzy WLSM was cited for aggregating these judgments in order to form a consensus group judgment; the MOI incorporated with a nonlinear programming model was used for calculating the fuzzy RPNs based on the group judgment; the partial order method based on fuzzy preference relations was employed for the final ranking of failure modes according to their scores of fuzzy RPNs.
Abdelgawad and Fayek (2010) extended the application of FMEA to risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP. In the study, severity (S) referred to as impact (I) and had three dimensions: cost impact (CI), time impact (TI) and scope/quality impact (SI). Fuzzy AHP was conducted to aggregate CI, TI and SI into a single variable entitled aggregated impact (AI). Based on the assigned values for O and D together with the calculated AI, fuzzy FMEA expert system supported by fuzzy if-then rules was used to analyze and prioritize different risk events. Besides, a software system entitled “risk criticality analyzer” (RCA) was developed to implement the proposed framework.

Liu et al. (2011) proposed a risk priority model for FMEA using fuzzy evidential reasoning (FER) approach and grey theory. The FER approach was used to model the diversity and uncertainty of FMEA team members’ assessment information, and the grey relational analysis was utilized to determine the risk priorities of failure modes. The core of the proposed FMEA includes assessing risk factors using belief structures, synthesizing individual belief structures into group belief structures, aggregating defuzzified group belief structures into overall belief structure, establishing comparative series standard series, obtaining the difference between comparative series and standard series, computing grey relational coefficient and degree of relation and ranking the failure modes using the degree of relation.
Chang and Cheng (2011, 2010) and Chang (2009) argued that, when each cause of failure is assigned to only one potential failure mode, the risk ranking orders obtained by DEMATEL approach (Seyed-Hosseini et al., 2006) correspond with the ones obtained by the conventional RPN method. In order to solve the problem, Chang (2009) proposed a general RPN methodology, which combines the ordered weighted geometric averaging (OWGA) operator and the DEMATEL approach for prioritization of failures in a product FMEA; Chang and Cheng (2010) proposed a technique combining the intuitionistic fuzzy set (IFS) and DEMATEL approach to evaluate the risk of failure, and Chang and Cheng (2011) proposed an algorithm, which utilizes fuzzy ordered weighted averaging (OWA) operator and the DEMATEL approach, to evaluate the orderings of risk for failure problems.
Chang and Wen (2010) also proposed a technique, combining 2-tuple and the OWA operator for prioritization of failures in a product design failure mode and effect analysis (DFMEA). The 2-tuple method was used to solve the problem that the conventional RPN method loses some information which the experts provide to have the valued information. The OWA operator was used to overcome the issue that the conventional RPN method does not consider the ordered weight, which may cause biased conclusions. A case of the color super twisted nematic (CSTN) was adopted to verify the proposed approach, and the result was compared with the conventional RPN and linguistic ordered weighted averaging operator (LOWA) methods.
Kutlu and Ekmeckioğlu (2012) considered a fuzzy approach, allowing experts to use linguistic variables for determining O, S and D, for FMEA by applying fuzzy TOPSIS integrated with fuzzy AHP. Fuzzy AHP was utilized to determine the weight vector of the three risk factors. Then by using the linguistic scores of risk factors for each failure modes, and the weight vector of risk factors, fuzzy TOPSIS was utilized to get the scores of potential failure modes, which were ranked to prioritize the failure modes.
Chen (2007) pointed out that when performing a FMEA, in addition to the measurement of risks, it is important to involve the utility of potential corrective actions. Therefore, they proposed a new approach to determine the priority order of FMEA, which aims to evaluate the structure of hierarchy and interdependence of corrective action by interpretive structural model (ISM), then to calculate the weight of a corrective action through the ANP, then to combine the utility of corrective actions and make a decision on improvement priority order of FMEA by utility priority number (UPN).

3.5. Other approaches
Gilchrist (1993) modified the conventional criticality assessment of FMECA and proposed an expected cost model: 

$$ EC = CnP_aP_f $$

where EC is the expected cost to the customer, C the failure cost, n the annual production quantity, P_f the probability of a failure and P_a the probability of the failure not to be detected. Ben-Daya and Raouf (1996) argued that the probabilities P_f and P_a in the expected cost model are not always independent and very difficult to esti-
mate at the design stage of a product, and the severity is completely ignored by the expected cost model. They therefore proposed an improved FMECA model which addressed Gilchrist’s criticisms and combined it with the expected cost model to provide a quality improvement scheme for the production phases of a product or service. von Ahsen (2008) argued that internally detected faults may also lead to very substantial failure costs and it is all ignored in conventional FMEA and Gilchrist’s approach. To deal with the problem, they proposed a cost-oriented FMEA, which not only includes the costs of external faults, but also the costs of internal faults and those of false positive inspection results in the evaluation of potential failures. In addition, Kmenta and Ishii (2004) proposed a scenario-based FMEA using expected cost, where probability and cost provide a consistent basis for risk analysis and decision making, and failure scenarios provide continuity across system levels and life cycle phases.

Dong (2007) provided a FMEA analysis tool based on fuzzy utility cost estimation to overcome the disadvantages of the traditional FMEA that the cost due to failure is not defined. This approach used utility theory and fuzzy membership functions for the assessment of O, S and D. The utility theory accounted for the nonlinear relationship between the cost due to failure and the ordinal ranking. The application of fuzzy membership functions represented the team opinions. The risk priority index (RPI) was developed for the prioritization of failure modes.

Rhee and Ishii (2003) introduced a life cost-based FMEA, which measures risk in terms of cost. Life cost-based FMEA was used for comparing and selecting design alternatives that can reduce the overall life cycle cost of a particular system. A Monte Carlo simulation was applied to the cost-based FMEA to account for the uncertainties in: detection time, fixing time, occurrence, delay time, down time and model complex scenarios.

Bevilaqua, Braglia, and Gabbielli (2000) proposed a methodology based on the integration between a modified FMECA and a Monte Carlo simulation as a method for testing the weights assigned to the measure of the RPNs. The modified RPN consisted of a weighted sum of six parameters (safety, machine importance for the process, maintenance costs, failure frequency, downtime length and operating conditions) multiplied by a seventh factor (the machine access difficulty), where the relative importance of the six attributes was estimated using pair-wise comparisons. By using the simulation of the weights, a deterministic assignment was not required and a stochastic final priority rank was obtained.

Xiao, Huang, Li, He, and Jin (2011) develop a FMEA method to combine multiple failure modes into single one, considering importance of failures and assessing their impact on system reliability. The proposed method was established upon the minimum cut sets (MCS) theory, which was incorporated into the traditional FMEA for assessing the system reliability in the presence of multiple failure modes. Additionally, they extended the definition of RPN by multiplying it with a weight parameter, which characterizes the importance of the failure causes within the system. Following the weighted RPN, the utility of corrective actions was improved and the improvement effect brought the favorable result in the shortest time.

Wang, Ruxton, and Labrie (1995) proposed an inductive bottom-up risk identification and estimation methodology combining FMECA and the Boolean representation method (BRM). It can be used to identify all possible system failure events and associated causes, and to assess the probabilities of occurrence of them particularly in those cases where multiple state variables and feedback loops are involved. In addition, the inductive BRM was used to process the information produced from FMECA to close the loop between risk identification and risk estimation.

Gandhi and Agrawal (1992) presented a method for FMEA of mechanical and hydraulic systems based on a digraph and matrix approach. A failure mode and effects digraph, derived from the structure of the system, was used to model the effects of failure modes of the system and, for efficient computer processing, matrices were defined to represent the digraph. A function characteristic of the system failure mode and effects was obtained from the matrix, which aids in the detailed analysis leading to the identification of various structural components of failure mode and effects. An index of failure mode and effects of the system was also obtained.

Shahin (2004) proposed an approach to enhance FMEA capabilities through its integration with Kano model. This approach determined severity and RPN through classifying severities according to customers’ perceptions, which supports the nonlinear relationship between frequency and severity of failure. Also a new index called “correction ratio” (Cr) was proposed to assess the corrective actions in FMEA. The proposed approach can enable managers/designers to prevent failures at early stages of design, based on customers who have not experienced their products/services yet.

Braglia, Fantoni, and Frosolini (2007) extended the quality functional deployment/house of quality (QFD/HoQ) concepts to FMEA and built a new operative tool, named house of reliability (HoR), which is able to translate the reliability requisites of the customer into functional requirements for the product in a structured manner, based on a failure analysis. It enhanced the standard FMEA analyses, introducing the most significant correlations among failure modes. Besides, using the results from HoR, a cost-worth analysis can be performed, making it possible to analyze and to evaluate the economical consequences of a failure. The integrated usage of QFD and FMEA can also be found in Tan (2003).

Sant’Anna (2012) proposed a method, derived from numerical evaluations on the criteria of security, frequency and detectability, of FMEA, a probabilistic priority measure for potential failures. The method proposed was based on treating the numerical initial measurements as estimates of location parameters of probability distributions, which allows for objectively taking into account the uncertainty inherent in such measurements and to compute probabilities of each potential failure being the most important according to each criterion. These probabilities were then combined into a global quality measure, which can be interpreted as a joint probability of choice of the potential failure.

4. Observations and findings

In this paper, 75 journal articles, which appeared in the period from 1992 to 2012, tackling the traditional FMEA problems using alternative approaches were collected. The identified approaches, including multi-criteria decision making, mathematical programming, artificial intelligence and their hybrids, have been summarized in Table 5 and described in the previous section. Based on these journal articles, some observations are made in the following subsections.

4.1. The most popular approach

As found in the previous sections, the category of method most frequently applied to FMEA was found to be AI with 40.0% of all the reviewed papers. MCDM approaches were the next most applied methods with 18 papers or 22.5%.

According to Table 5, the most popular approach is fuzzy rule-base system, followed by grey theory, cost based model, AHP/ANP and linear programming. The wide applicability of fuzzy rule-base system is because fuzzy logic and knowledge-based approach possess unique advantages. Compared to the conventional FMEA methodology, the fuzzy expert system provides the following advantages (Bowles & Peláez, 1995; Braglia et al., 2003a; Sharma et al., 2005; Tay & Lim, 2006a, 2006b, 2010; Xu et al., 2002):
4.2. Limitations of approaches

The last objective of this paper is to critically analyze the identified approaches, and try to find out some drawbacks. Instead of analyzing every single approach, the main focus of this section is confined to fuzzy rule-base system, which is the most popular approach. In essence, any fuzzy expert system is composed of three processes referred to as fuzzification, fuzzy inference and defuzzification. In fuzzy FMEA, the risk factors, i.e. O, S and D, are fuzzified or reduced, then the consequences of the two rules must be the same. This shows the fact that the expert cannot differentiate the two different failure modes from each other.

Although fuzzy inference technique has been widely used to enhance FMEA methodology, it still suffers from several limitations (Abdelgawad & Fayek, 2010; Braglia, 2000; Braglia et al., 2003a, 2003b; Tay & Lim, 2006a, 2010; Yang et al., 2008; Zhang & Chu, 2011):

- Ambiguous, qualitative or imprecise information, as well as quantitative data can be used in criticality/risk assessment and they are handled in a consistent manner.
- It permits to combine the occurrence, severity and detectability of failure modes in a more flexible and realistic manner.
- It allows the failure risk evaluation function to be customized based on the nature of a process or a product.
- The fuzzy knowledge-based system can fully incorporate engineers’ knowledge and expertise in the FMEA analysis and substantial cost savings can thus be realized.

4.2.1. Distribution of journal articles

Fig. 1. Distribution of the reviewed articles.

To avoid building a big if-then rule base, some fuzzy FMEA approaches utilize a reduced if-then rule base. However, this causes some new problems (Wang et al., 2009b):

- If two if-then rules with different antecedents can be combined or reduced, then the consequences of the two rules must be the same. When their judgments are inconsistent, it is nearly impossible to combine or reduce rules.
- Reduced rules will be incomplete if they are not reduced from a complete if-then rule base. Any inference from an incomplete rule base will be biased or even wrong because some knowledge cannot be learned from such an incomplete rule base.
- If a complete if-then rule base can be built using expert knowledge, then failure modes should be prioritized into different priority categories rather than be given a full priority ranking.

### Table 6

The reviewed weighting methods for risk factors.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Weighting methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>Chang (2009), Chang and Cheng (2011), Chang and Wen (2010), Chin et al. (2005a), Chang and Sun (2009), Garcia et al. (2005), Xiao et al. (2011)</td>
</tr>
</tbody>
</table>
4.3.2. Weighting methods for risk factors

The most commonly pointed shortcoming around traditional FMEA in the reviewed literature was that the relative importance among O, S and D is not taken into consideration. Forty-five papers (60.0%) addressed this problem by either subjective methods or objective weighting methods. Therefore, it is necessary to review the weighting methods used in these papers. Generally, the weighting methods are classified into three categories: subjective weighting method, objective weighting method and combination weighting method (Wang, Jing, Zhang, & Zhao, 2009a). The methods have been applied in FMEA are shown in Table 6.

From Table 6, it can be observed that only subjective weighting and objective weighting methods were employed to elicit the weights of risk factors in FMEA. The literature about combination weighting methods applied in FMEA are scarce in the reviewed papers while the combination weighting methods were gradually applied to other evaluation systems, such as social, energy and ecological systems.

5. Conclusions and suggestions for future work

Due to the disadvantages of the traditional FMEA and the uncertainty of the risk factors, many risk priority models were proposed for prioritization of failure modes aiming at accurate and robust risk evaluation. This paper is based on a literature review on the alternative methodologies for risk evaluation in FMEA from 1992 to 2012. To our best knowledge, this is the first comprehensive research paper reviewing the literature that solve the problems and improve the effectiveness of FMEA. This paper has set out to provide a framework of the FMEA literature as an aid to the categorization of research in this field.

First, it was observed that the traditional FMEA based on crisp RPN is not supportive and robust enough in priority ranking of failure modes. Of the shortcomings described in the reviewed literature, the ones that have received significant attention from the literature can be seen as being risk factor and RPN related issues. For instance, the relative importance among the three factors (O, S and D) is not considered; different combinations of O, S and D may produce exactly the same value of RPN; and the three factors are difficult to be precisely estimated.

Second, it was found that numerous alternative approaches were proposed to overcome the shortcoming of the traditional FMEA. They are all capable of addressing some of the problems associated with the traditional RPN method. It can be observed from the surveyed literature that fuzzy rule-base system is the most popular method for prioritizing the failure modes, followed by grey theory, cost based model, AHP/ANP and linear programming.

Third, the fuzzy rule based methods proposed in the FMEA literature improve the accuracy of the failure criticality analysis by compromising the easiness and transparency of the conventional method. But some doubts remain concerning an actual applicability of fuzzy rule-base system to real-life circumstances, by reason of the difficulties which arise during the fuzzy model design, i.e. in defining the (numerous) rules and membership functions required by this methodology.

The intention of this paper is to systematically classify the existing literature which applied different methods to enhance FMEA performance and provide a direction for future research so as to further solve the known deficiencies of the traditional FMEA. The main suggestions for future work are as follows:

- There is need to split risk factors to reduce their vagueness and add other risk factors in the determination of risk priority of failure modes. For example, severity was split into three sub-

As long as risk factor selection, weighting method and risk priority method are appropriate and suitable to the specific risk evaluation problems, FMEA can become a more effective and powerful tool for safety and reliability analysis of systems, processes, designs and services in a variety of industries.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eswa.2012.08.010.

References


