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Review

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

Hu-Chen Liu [a], Long Liu [b,*], Nan Liu [c]

[a] Department of Industrial Engineering and Management, Tokyo Institute of Technology, Tokyo 152-8552, Japan
[b] College of Design and Innovation, Tongji University, Shanghai 200092, PR China
[c] School of Management, Chongqing Jiaotong University, Chongqing 400074, PR China

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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.

1. Introduction

Failure mode and effects analysis (FMEA), first developed as a formal design methodology in the 1960s by the aerospace industry (Bowles & Peláez, 1995), has proven to be a useful and powerful tool in assessing potential failures and preventing them from occurring (Sankar & Prabhu, 2001). FMEA is an analysis 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 (Stamatis, 1995). When it is used for a criticality analysis, it is also referred to as failure mode, effects and criticality analysis (FMECA). The main objective of FMEA is to identify potential failure modes, evaluate the causes and effects of different component failure modes, and determine what could eliminate or reduce the chance of failure. The results of the analysis can help analysts to identify and correct the failure modes that have a detrimental effect on the system and improve its performance during the stages of design and production. Since its introduction as a support tool for designers, FMEA has been extensively used in a wide range of industries, including aerospace, automotive, nuclear, electronics, chemical, mechanical and medical technologies industries (Chang & Cheng, 2011; Chin, Wang, Poon, & Yang, 2009b; Sharma, Kumar, & Kumar, 2005).

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.

* Corresponding author. Address: College of Design and Innovation, Tongji University, 1239 Siping Road, Shanghai 200092, PR China. Tel./fax: +86 (0) 21 6598 3432.

E-mail addresses: huchenliu@foxmaill.com (H.-C. Liu), liulong@tongji.edu.cn (L. Liu), liunan@cqjtu.edu.cn (N. Liu).

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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

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

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. 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 recalculated 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 1 and the most important ones could be found in Table 4.

Table 1
Suggested ratings for the occurrence of a failure mode (Chang, 2009; Chang & Cheng, 2010; Chang & Sun, 2009; Chang & Wen, 2010; Chang et al., 2010; Ford Motor Company, 1988; Liu et al., 2012; Sankar & Prabhu, 2001; Seyed-Hosseini et al., 2006).

Probability of failure	Possible failure rates	Rank
Extremely high: failure almost inevitable	⩾ in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2000	4
Low	1 in 15,000	3
Remote	1 in 150,000	2
Nearly impossible	⩽1 in 1,500,000	1

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 with the maximum risk priority code (RPC). If two or more failure modes have the same RPC a more detailed selection was provided to discriminate their relative ranking.

Chin et al. (2009b) proposed an FMEA using the group-based evidential reasoning (ER) approach to capture FMEA team members' diversity opinions and prioritize failure modes under different types of uncertainties such as incomplete assessment, ignorance and intervals. The risk priority model was developed 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

Table 2
Suggested ratings for the severity of a failure mode (Chang, 2009; Chang & Cheng, 2010; Chang & Sun, 2009; Chang & Wen, 2010; Chang et al., 2010; Ford Motor Company, 1988; Liu et al., 2012; Sankar & Prabhu, 2001; Seyed-Hosseini et al., 2006).

Effect	Criteria: severity of effect	Rank
Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Table 3
Suggested ratings for the detection of a failure mode (Chang, 2009; Chang & Cheng, 2010; Chang & Sun, 2009; Chang & Wen, 2010; Chang et al., 2010; Ford Motor Company, 1988; Liu et al., 2012; Sankar & Prabhu, 2001; Seyed-Hosseini et al., 2006).

Detection	Criteria: likelihood of detection by design control	Rank
Absolute uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainly detect a potential cause of failure or subsequent failure mode	1

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. On the other hand, Hu, Hsu, Kuo, and Wu (2009) presented a green component risk priority number (GC-RPN) to analyze the risks of green components to hazardous substance. Fuzzy AHP was applied to determine the relative weightings of risk factors. Then the GC-RPN was calculated for each one of the components to identify and manage the risks derived from them.

Zammori and Gabbrielli (2011) presented an advanced version of the FMECA, called analytic network process (ANP)/RPN, which enhances the capabilities of the standard FMECA taking into account possible interactions among the principal causes of failure in the criticality assessment. According to the ANP/RPN model, O, S and D were split into sub-criteria and arranged in a hybrid (hierarchy/network) decision structure that, at the lowest level, contains the causes of failure. Starting from this decision-structure, the RPN was computed by making pairwise comparisons. In order to clarify and to make evident the rational of the final results a graphical 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

Table 4
The major shortcomings of FMEA.

Shortcomings	Literature	Total number
The relative importance among O, S and D is not taken into consideration	Wang et al. (2009b), Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Zhang and Chu (2011), Yang et al. (2008), Braglia et al. (2003a, 2003b), Sharma et al. (2005, 2007a, 2007b, 2007c, 2007d, 2008a, 2008b, 2008c), Sharma and Sharma (2012, 2010), Chang and Cheng (2011, 2010), Chang and Wen (2010), Chang et al. (2010, 1999, 2001), Seyed-Hosseini et al. (2006), Tay and Lim (2010, 2006a), Keskin and Zkan (2009), Pillay and Wang (2003), Bowles and Peláez (1995), von Ahsen (2008), Carmignani (2009), Xiao et al. (2011), Franceschini and Galetto (2001), Nepal et al. (2008), Sankar and Prabhu (2001), Zammori and Gabbrielli (2011), Abdelgawad and Fayek (2010), Shahin (2004), Puente et al. (2002), Garcia et al. (2005), Chang and Sun (2009)	45
Different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally different	Wang et al. (2009b), Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Zhang and Chu (2011), Yang et al. (2008), Braglia et al. (2003b), Sharma et al. (2005, 2007a, 2007b, 2007c, 2007d, 2008a, 2008b, 2008c), Sharma and Sharma (2012, 2010), Tay and Lim (2010, 2006a), Keskin and Zkan (2009), Pillay and Wang (2003), Chen (2007), von Ahsen (2008), Carmignani (2009), Franceschini and Galetto (2001), Chang et al. (1999, 2001), Shahin (2004), Puente et al. (2002), Chang and Sun (2009)	33
The three risk factors are difficult to be precisely evaluated	Wang et al. (2009b), Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Yang et al. (2008), Braglia et al. (2003a, 2003b), Sharma et al. (2005), Chang et al. (2010), Xu et al. (2002), Braglia (2000), Yang et al. (2011), Chen and Ko (2009a, 2009b), Zammori and Gabbrielli (2011), Abdelgawad and Fayek (2010), Garcia et al. (2005)	21
The mathematical formula for calculating RPN is questionable and debatable	Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Braglia et al. (2003a, 2003b), Geum et al. (2011), Chang et al. (1999, 2001), Puente et al. (2002), Ben-Daya and Raouf (1996), Gilchrist (1993)	14
The conversion of scores is different for the three risk factors	Chin et al. (2009b), Liu et al. (2011), Braglia et al. (2003a, 2003b), Chen (2007), von Ahsen (2008), Carmignani (2009), Chang et al. (1999, 2001), Sankar and Prabhu (2001), Puente et al. (2002), Ben-Daya and Raouf (1996), Gilchrist (1993)	13
The RPN cannot be used to measure the effectiveness of corrective actions	Yang et al. (2008), Braglia et al. (2003b, 2007), Pillay and Wang (2003), Chen (2007), Carmignani (2009), Chang et al. (1999, 2001), Shahin (2004), Puente et al. (2002), Ben-Daya and Raouf (1996), Gilchrist (1993)	12
RPNs are not continuous with many holes	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)	10
Interdependencies among various failure modes and effects are not taken into account	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)	10
The mathematical form adopted for calculating the RPN is strongly sensitive to variations in risk factor evaluations	Chin et al. (2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Yang et al. (2008), Braglia et al. (2003a, 2003b), Chang (2009)	9
The RPN elements have many duplicate numbers	Gargama and Chaturvedi (2011), Chang and Cheng (2011, 2010), Chang et al. (2010), Chang (2009), Seyed-Hosseini et al. (2006), Sankar and Prabhu (2001), Garcia et al. (2005), Chang and Sun (2009)	9
The RPN considers only three risk factors mainly in terms of safety	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)	9

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 diagraph, 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.

Table 5
Classification of risk evaluation methods in FMEA.

Categories	Approaches	Literature	Total number
MCDM (22.50%)	ME-MCDM	Franceschini and Galetto (2001)	1
	Evidence theory	Chin et al. (2009b), Yang et al. (2011)	2
	AHP/ANP	Braglia (2000), Carmignani (2009), Hu et al. (2009), Zammori and Gabbrielli (2011)	4
	Fuzzy TOPSIS	Braglia et al. (2003b)	1
	Grey theory	Chang et al. (1999, 2001), Sharma et al. (2008b, 2007d), Pillay and Wang (2003), Sharma and Sharma (in press), Geum et al. (2011)	7
	DEMATEL	Seyed-Hosseini et al. (2006)	1
	Intuitionistic fuzzy set ranking technique	Chang et al. (2010)	1
	VIKOR	Liu et al. (2012)	1
Mathematical programming (8.75%)	Linear programming	Wang et al. (2009b), Gargama and Chaturvedi (2011), Chen and Ko (2009a, 2009b)	4
	DEA /Fuzzy DEA	Garcia et al. (2005), Chang and Sun (2009), Chin et al. (2009a)	3
Artificial intelligence (40.00%)	Rule-base system	Sankar and Prabhu (2001)	1
	Fuzzy rule-base system	Bowles and Peláez (1995), Moss and Woodhouse (1999), Xu et al. (2002), Zafiropoulos and Dialynas (2005), Chin et al. (2008), Nepal et al. (2008), Puente et al. (2002), Pillay and Wang (2003), Yang et al. (2008), Gargama and Chaturvedi (2011), Braglia and Bevilacqua (2000), Braglia et al. (2003a), Tay and Lim (2006a, 2010), Sharma et al. (2005, 2007a 2007b, 2007c, 2007d, 2008a, 2008b, 2008c), Sharma and Sharma (2010, 2012), Guimarães and Franklin Lapa (2004), Guimarães and Lapa (2004, 2006, 2007), Guimarães et al. (2011)	29
	Fuzzy ART algorithm	Keskin and Zkan (2009)	1
	Fuzzy cognitive map	Peláez and Bowles (1996)	1
Integrated approaches (11.25%)	Fuzzy AHP-Fuzzy rule-base system	Abdelgawad and Fayek (2010)	1
	WLSM-MOI-Partial ranking method	Zhang and Chu (2011)	1
	OWGA operator-DEMATEL	Chang (2009)	1
	IFS-DEMATEL	Chang and Cheng (2010)	1
	Fuzzy OWA operator-DEMATEL	Chang and Cheng (2011)	1
	2-tuple-OWA operator	Chang and Wen (2010)	1
	FER-Grey theory	Liu et al. (2011)	1
	Fuzzy AHP-fuzzy TOPSIS	Kutlu and Ekmekçioğlu (2012)	1
	ISM-ANP-UPN	Chen (2007)	1
Other approaches (17.50%)	Cost based model	Gilchrist (1993), Ben-Daya and Raouf (1996), von Ahsen (2008), Kmenta and Ishii (2004), Dong (2007), Rhee and Ishii (2003)	6
	Monte Carlo simulation	Bevilacqua et al. (2000)	1
	Minimum cut sets theory (MCS)	Xiao et al. (2011)	1
	Boolean representation method (BRM)	Wang et al. (1995)	1
	Digraph and matrix approach	Gandhi and Agrawal (1992)	1
	Kano model	Shahin (2004)	1
	Quality functional deployment (QFD)	Braglia et al. (2007), Tan (2003)	2
	Probability theory	Sant'Anna (2012)	1

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 priority 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 α-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 α 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.

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 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 FMECA, which uses linguistic variables to describe O, S, 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 Dialynas (2005) presented a fuzzy FMECA 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 (FuRBaR) 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 Bevilacqua (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 researches 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) was 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 Ekmekçioğlu (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: $EC = CnP_fP_d$, 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_d the probability of the failure not to be detected. Ben-Daya and Raouf (1996) argued that the probabilities P_f and P_d in the expected cost model are not always independent and very difficult to estimate 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.

Bevilacqua, Braglia, and Gabbrielli (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):

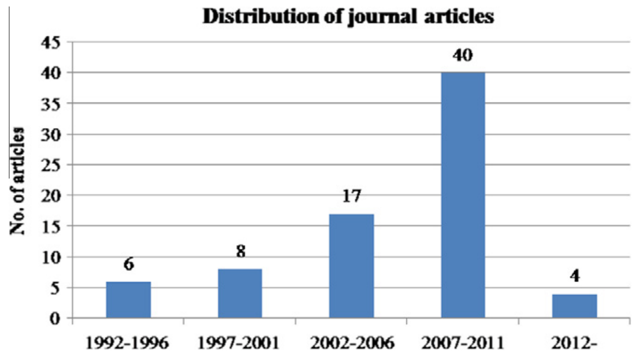

Fig. 1. Distribution of the reviewed articles.

- 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. 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 using appropriate membership functions to determine degree of membership in each input class. The resulting fuzzy inputs are evaluated in fuzzy inference engine, which makes use of well-defined rule base consisting of if-then rules and fuzzy logic operations to determine riskiness level of the failure. The fuzzy conclusion is then defuzzified to get risk priority number.

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):

- It is difficult to define appropriate membership functions for the risk factors and risk priority level. Besides, any modification to the linguistic terms, for instance, using seven linguistic terms to define D instead of five, will require re-elicitation of the relevant membership functions.
- It suffers from the combinatorial rule explosion problem, which causes the fuzzy RPN model often has a large number of rules. The larger the number of rules provided by the experts, the better the prediction accuracy of the fuzzy RPN model.
- The construction of a fuzzy if-then rule base is not an easy task which requires experts to make a vast number of judgments and will be highly costly and time-consuming.
- The fuzzy if-then rules with the same consequence but different antecedents are unable to be distinguished from one another. As a result, the failure modes characterized by these fuzzy if-then rules will be unable to be prioritized or ranked.
- It is difficult to deal with complex calculations for producing "precise" risk results without losing too much information in the process of fuzzy inference.
- It is difficult to design appropriate software packages to realize the instant communication between risk input and output, and failure priority ranking.

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. This shows the fact that the expert cannot differentiate the two different failure modes from each other.
- Different experts may have different knowledge and judgments. 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.

4.3. Other observations

4.3.1. Distribution of journal articles

The distribution of the 75 journal articles between 1992 and 2012 (by July 08, 2012) is shown in Fig. 1. It is observed that there is a significant growth in the study of dealing with traditional FMEA problems using various alternative approaches from the first 5 years (1992–1996) to the recent 5 years (2007–2011), 6 vs. 40. The growth could also mark a movement away from the conventional RPN method and towards increased use of MCDM, MP, AI and their combinations. It is anticipated that the number will keep increasing in the coming years because of the importance of FMEA in improving the reliability of the systems and the increased interest in FMEA by researchers and practitioners.

Table 6
The reviewed weighting methods for risk factors.

Categories	Weighting methods	Literature	Total number
Direct given	–	Geum et al. (2011), Chang and Cheng (2010), Chin et al. (2009b), Chen and Ko (2009a, 2009b), Pillay and Wang (2003), Chang et al. (2001, 1999)	8
Subjective weighting	Direct assessment by experts	Liu et al. (2011, 2012), Wang et al. (2009b), Zhang and Chu (2011), Gargama and Chaturvedi (2011), Braglia et al. (2003b)	6
	AHP/ANP	Kutlu and Ekmekçioğlu (2012), Abdelgawad and Fayek (2010), Hu et al. (2009), Sharma and Sharma (in press), Zammori and Gabbrielli (2011), Carmignani (2009), Sharma et al. (2008b, 2007d), Braglia (2000), Bevilacqua et al. (2000)	10
Objective weighting	Ordered weight	Chang (2009), Chang and Cheng (2011), Chang and Wen (2010)	3
	DEA	Chin et al. (2009a), Chang and Sun (2009), Garcia et al. (2005)	3
	Minimum cut set	Xiao et al. (2011)	1

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 FEMA 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-risk factors: damages, production and maintenance costs in Zammori and Gabbrielli (2011) and expected cost was taken into account during failure analysis in Braglia (2000).
- The proper assessment of risk factor weights plays an essential role in the criticality analysis because it may affect the rankings of the failure modes. However, subjective weightings are still the most popular in weighting methods and AHP method is prevalent because it is relatively easier, flexible and requires less cognitive skills. The objective and combination weighting methods should be applied to the risk assessment in FMEA because they evaluate the relative importance objectively without decision-makers.
- MCDA approaches are the second most methods employed to prioritize failure modes considering multi-criteria. There is a trend in using more than just one MCDM model to enhance the efficacy and empirical validity of risk assessment results. Recent literature also shows a shift towards using integrated methods (e.g. AHP has been combined with other models), so that synergies can be maximized.

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.

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