Chapter 2
FMEA Using Uncertainty Theories and MCDM Methods

To resolve the shortcomings of the conventional RPN method, a great number of studies have been conducted on the improvement of FMEA and a variety of alternative approaches have been proposed. Liu et al. (2013) first reviewed the approaches employed to enhance the performance of FMEA and proposed a framework to categorize the improved models for risk evaluation in FMEA. In this chapter, we update the results in Liu et al. (2013) and provide a systematic review of those academic works attempting to deal with the deficiencies of the traditional FMEA based on uncertainty theories and MCDM methods. Related articles appearing in the international journals from 1992 to 2016 are gathered and analyzed. Based on the 64 journal articles collected, the specific objectives of this chapter are to summarize the MCDM methods that have been used in the FMEA literature and to show the current research trends and future research directions in this field of study.

2.1 Research Methodology

This chapter presents the results of an extensive literature survey on the risk evaluation methods in FMEA using uncertainty theories and MCDM methods. For this purpose, we searched in Scopus database for academic articles published between 1992 and 2016. The keywords "FMEA" and "failure mode and effect analysis" were used for searching in "abstract, title, and keywords" for journal papers. As a result, a total of 849 document results were identified from the Scopus database, of which 64 fall under the scope of this review after the title, abstract, and full-text screening. 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

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reported on a MCDM method or technique that specifically aims at overcoming some of the shortcomings of the traditional FMEA.

A variety of MCDM-based risk priority models are found in the literature to improve the criticality analysis process of FMEA. Depending on the MCDM methods used, the reviewed papers are roughly grouped into four categories: the ones using distance-based MCDM methods (16 articles), the ones using compromise ranking MCDM methods (11 articles), the ones using outranking MCDM methods (3 articles), the ones using pairwise comparison MCDM methods (8 articles), the ones using other MCDM methods (18 articles), and the ones based on hybrid MCDM methods (8 articles). The classification scheme of these FMEA articles is shown in Table 2.1. In what follows, we more specifically go into the references and show what has been done.

Table 2.1 Classification of MCDM-based FMEA models

Categories	Approaches	Reference	Percentage (%)
Distance-based MCDM methods	Distance measure	Liu et al. (2014c, e)	25.0
	GRA	Geum et al. (2011), Liu et al. (2015a, d), Chang et al. (1999, 2001), Pillay and Wang (2003), Sharma et al. (2007, 2008), Sharma and Sharma (2012, 2015), Moon et al. (2013), Tsai and Yeh (2015); Panchal and Kumar (2016), Zhou and Thai (2016)	
Compromise ranking MCDM methods	VIKOR	Liu et al. (2012), Safari et al. (2016), Emovon et al. (2015)	17.2
	TOPSIS	Braglia et al. (2003), Helvacioglu and Ozen (2014), Sachdeva et al. (2009), Song et al. (2013, 2014), Chang (2015), Liu et al. (2015d), Vahdani et al. (2015)	
Outranking MCDM methods	QUALIFLEX	Liu et al. (2016b)	4.7
	ELECTRE	Liu et al. (2016a)	
	PROMETHEE	Lolli et al. (2015)	
Pairwise comparison MCDM methods	AHP	Braglia (2000), Chang (2016), Carmignani (2009), Hu et al. (2009), Ilangkumaran et al. (2014), Abdelgawad and Fayek (2010)	12.5
	ANP	Zammori and Gabbrielli (2011), Hsu et al. (2013)	

(continued)

Table 2.1 (continued)

Categories	Approaches	Reference	Percentage (%)
Other MCDM methods	ME-MCDM	Franceschini and Galetto (2001)	28.1
	GFEA	Jenab and Dhillon (2005)	
	MULTIMOORA	Liu et al. (2014b), Zhao et al. (2016)	
	COPRAS-G	Adhikary et al. (2014)	
	ER	Chin et al. (2009), Gargama and Chaturvedi (2011), Du et al. (2016)	
	DEMATEL	Seyed-Hosseini et al. (2006), Chang (2009), Chang and Cheng (2010), Chang and Cheng (2011), Chang (2014), Li et al. (2012, 2015c), Wang et al. (2016)	
	Digraph and matrix	Gandhi and Agrawal (1992), Liu et al. (2014a)	
Hybrid MCDM methods	AHP and TOPSIS	Kutlu and Ekmekçioğlu (2012), Ekmekçioğlu and Kutlu (2012)	12.5
	VIKOR and AHP	Liu et al. (2015e)	
	VIKOR, DEMATEL, and AHP	Liu et al. (2015b)	
	FER and GRA	Liu et al. (2011)	
	ER and TOPSIS	Du et al. (2014)	
	GRA and DEMATEL	Chang et al. (2013)	
	TOPSIS and DEMATEL	Chang et al. (2014)	

2.2 MCDM Methods for FMEA

2.2.1 Distance-Based MCDM Methods

Liu et al. (2014c) developed an alternative risk assessment methodology using the intuitionistic fuzzy hybrid weighted Euclidean distance (IFHWED) operator for risk evaluation and prioritization of failure modes in FMEA. Particularly, both subjective and objective weights of risk factors are considered using the developed method. Liu et al. (2014e) evaluated the risk of failure modes by the interval 2-tuple hybrid weighted distance (ITHWD) measure and proposed a new risk priority to improve the performance of the traditional FMEA. The new model can not only consider the subjective and objective weights of risk factors but also handle the uncertainty and diversity of FMEA team members' assessment information in the risk prioritization process.

Geum et al. (2011) proposed a systematic approach for identifying and evaluating potential failures based on service-specific FMEA and grey relational analysis (GRA) method. Firstly, the service-specific FMEA was constructed to incorporate the multilateral service-specific characteristics to FMEA. Next, the GRA was applied for calculating the risk score of each dimension (i.e., *O*, *S*, and *D*) and the final risk priority of each service failure mode. Liu et al. (2015a) presented a novel FMEA approach combining interval 2-tuple linguistic variables with GRA to capture FMEA team members' diversity assessments and improve the effectiveness of the traditional FMEA, and Liu et al. (2014d) proposed a new risk priority model for the risk evaluation in FMEA based on D numbers and an improved GRA method, called grey relational projection (GRP).

Chang et al. (1999) proposed a FMEA approach for finding the RPNs based on fuzzy method and grey theory, where the GRA is applied to determine the risk priority of potential causes. Chang et al. (2001) also utilized the grey theory for FMEA, but the degrees of relational were computed through the traditional crisp scores 1–10 for the risk factors *O*, *S*, and *D*. Other applications of GRA method for the prioritization of failure modes in FMEA can be found in Pillay and Wang (2003), Sharma et al. (2007, 2008), Sharma and Sharma (2012, 2015), Moon et al. (2013), Tsai and Yeh (2015), Panchal and Kumar (2016), Zhou and Thai (2016).

2.2.2 *Compromise Ranking MCDM Methods*

Liu et al. (2012) determined the risk priorities of failure modes with an extended VIKOR method under fuzzy environment. In this study, the linguistic terms expressed in trapezoidal fuzzy numbers were used to assess the ratings for risk factors and an extension of the VIKOR was utilized to determine risk priorities of the identified failure modes in FMEA. Because of the drawbacks of the traditional FMEA, Safari et al. (2016) employed the fuzzy VIKOR-based FMEA to evaluate enterprise architecture (EA) risks to facilitate EA deployment in an organization, and Emovon et al. (2015) used an enhanced FMEA model integrating an averaging technique with the VIKOR to prioritize the risk of failure modes for marine machinery systems.

Braglia et al. (2003) first used the fuzzy technique for order preference by similarity to ideal solution (TOPSIS) approach for prioritizing failure modes in FMEA, in which the ranking for failure causes is determined based on the measurement of the Euclidean distance of an alternative from an ideal goal. Helvacioglu and Ozen (2014) proposed a risk priority framework to overcome the shortcomings of the traditional FMEA through fuzzy TOPSIS and applied it to yacht system design. Based on the TOPSIS, Sachdeva et al. (2009) presented an alternative FMEA approach for prioritizing failure modes, which considers the risk factors for failure occurrence, non-detection, maintainability, spare parts, economic safety, and economic cost and employs the Shannon entropy concept to compute the objective weights of the six risk factors. Song et al. (2013) developed a failure evaluation

structure based on fuzzy TOPSIS and comprehensive weighting method to improve the effectiveness of FMEA technique, and Song et al. (2014) proposed a FMEA approach using rough set theory and group TOPSIS method for ranking the risk of failure modes under subjective and uncertain environment.

Liu et al. (2015d) introduced a new modified TOPSIS method, namely the intuitionistic fuzzy hybrid TOPSIS approach, to determine the risk priorities of the failure modes identified in FMEA. Vahdani et al. (2015) proposed a modified version of FMEA by integrating fuzzy belief structure and TOPSIS to alleviate the drawbacks and improve the risk evaluation process of the traditional FMEA. Chang (2015) proposed a risk assessment method based on soft TOPSIS approach to solve the risk assessment problem in FMEA under a linguistic environment.

2.2.3 Outranking MCDM Methods

Liu et al. (2016a) described the application of an ELECTRE-based outranking approach for FMEA within the interval 2-tuple linguistic environment. Considering different types of FMEA team members' assessment information, a hybrid averaging operator was employed to construct the group assessment matrix and a modified ELECTRE method was used to analyze the group interval 2-tuple linguistic data to determine the risk ranking of failure modes. Liu et al. (2016b) developed a new risk priority model for FMEA by integrating hesitant 2-tuple linguistic term sets and an extended QUALIFLEX approach. In this model, the concept of hesitant 2-tuple linguistic term sets was presented to express various uncertainties in the assessment information of FMEA team members and a multiple objective optimization model based on GRA method was constructed to determine the relative weights of risk factors with incomplete weight information. Finally, the extended QUALIFLEX approach with an inclusion comparison method was suggested for prioritizing failure modes incorporating interrelationship between failure modes, cost of failure, and corrective action cost as additional risk factors. Lolli et al. (2015) proposed a MCDM method for FMEA based on the PROMETHEE notation to sort failure modes into priority classes, in which FMEA team members are asked to establish the reference profiles on each risk factor according to their experience and skills for obtaining the global classification of the failure modes.

2.2.4 Pairwise Comparison MCDM Methods

Braglia (2000) developed a multi-attribute failure mode analysis (MAFMA) model based on analytic hierarchy process (AHP) technique, which considers the risk factors (O, S, D, and expected cost) as decision criteria, possible causes of failure as decision alternatives, and the priority ranking of failure causes as decision goal. Then, following the AHP procedure, all the possible causes of failure are evaluated

and ranked. Making reference to Braglia (2000), Chang (2016) proposed an approach that integrates MAFMA and the 2-tuple representation method for risk assessment and prioritization. Carmignani (2009) presented a priority-cost-based FMEA approach based on a new interpretation of RPN, the AHP technique, and the new variable of profitability, in which the AHP is used to determine the different weights of risk factors. Hu et al. (2009) utilized fuzzy AHP to determine the relative weights of risk factors and proposed a green component risk priority number (GC-RPN) to analyze the risk of green components to hazardous substance, and Ilangkumaran et al. (2014) used fuzzy AHP to compute the risk factor weights and developed an evaluation model based on FMEA and fuzzy AHP for assessing the risk priority of the critical components in a paper industry. Abdelgawad and Fayek (2010) used fuzzy expert system and fuzzy AHP to address the limitations of the traditional calculation of RPN and extended the application of FMEA to risk criticality assessment in the construction industry.

Zammori and Gabbrielli (2011) presented a risk assessment procedure by integrating FMEA and analytic network process (ANP) taking into account possible interactions among the principal causes of failure in the criticality assessment. According to the model, O, S, and D were split into subcriteria and arranged in a hybrid (hierarchy/network) decision structure to compute the RPN. The causes of failure were included in the lowest level of the structure, and their effects and the strengths of their dependencies were assessed via pairwise judgments. Hsu et al. (2013) utilized the FMEA to construct a materiality analysis model for determining material issues in sustainability reporting, in which the ANP is employed to determine the weights of risk factors and a RPN of materiality analysis is calculated for material issues of sustainability reporting to rank them in accordance with stakeholder needs.

2.2.5 *Other MCDM Methods*

Franceschini and Galetto (2001) presented a multi-expert MCDM (ME-MCDM) method to calculate the risk priority levels of the failure modes in FMEA, which is able to deal with the information provided by the design team without necessitating an arbitrary and artificial numerical conversion. Jenab and Dhillon (2005) reported a group-based failure effect analysis (GFEA) method to mitigate the problems of the conventional RPN approach, which uses group decision-making technique to study the failure risk category with uncertain information and uses the compensated operators to allow the trade-off among risk factors.

Liu et al. (2014b) proposed a risk priority model for evaluating the risk of failure modes based on fuzzy set theory and MULTIMOORA method, in which the risk factors and their relative weights are evaluated using fuzzy ratings, and the failure modes are ranked through an extended MULTIMOORA method. Zhao et al. (2016) presented a new approach for FMEA based on interval-valued intuitionistic fuzzy sets (IVIFSs) and MULTIMOORA method to handle the uncertainty and vagueness

from FMEA team members' subjective assessments and to get a more accurate ranking of failure modes identified in FMEA. In the proposed approach, the interval-valued intuitionistic fuzzy continuous weighted entropy was applied for risk factor weighting. Adhikary et al. (2014) substituted the conventional RPN estimation method by grey complex proportional assessment (COPRAS-G) and presented a multi-criteria FMEA for coal-fired thermal power plants using uncertain data. In this model, the weight of each risk factor was calculated based on the Shannon entropy concept.

Chin et al. (2009) presented a risk priority model for FMEA using the group-based evidential reasoning (ER) approach to capture FMEA team members' diversity judgments and prioritize failure modes under different types of uncertainties such as incomplete assessment, ignorance, and intervals. The belief structures in evidence theory were also used by Gargama and Chaturvedi (2011) to handle the diversity and uncertainty in the opinions of FMEA team members. To improve the model of Chin et al. (2009), Du et al. (2016) proposed an evidential downscaling method to make FMEA more efficient in practical applications.

Seyed-Hosseini et al. (2006) used the decision-making trial and evaluation laboratory (DEMATEL) technique for reprioritization of failure modes in a system FMEA. The proposed methodology prioritizing failures in terms of direct/indirect relationships between them is suitable for large systems with many subsystems or components. Later, Chang (2009) proposed a methodology which combines the ordered weighted geometric averaging (OWGA) operator and the DEMATEL to evaluate the risk of failures in FMEA; Chang and Cheng (2010) proposed an algorithm integrating intuitionistic fuzzy sets (IFSs) and the DEMATEL for prioritization of failures, Chang and Cheng (2011) suggested an approach which utilizes fuzzy ordered weighted averaging (OWA) operator and the DEMATEL to evaluate the orderings of risk for failure problems, and Chang (2014) presented a soft set-based DEMATEL technique for the prioritization of failures in a product FMEA. To handle uncertain or vague data sets, Li et al. (2012) proposed a methodology by combining evidence theory, IFS, and the DEMATEL approach to make risk assessment for an FMEA system. Recently, Liu et al. (2015c) proposed an integrated approach for FMEA based on fuzzy weighted average (FWA) and fuzzy DEMATEL that could not only cope with the interdependencies among various failure modes but also avoid the shortcomings of the previous DEMATEL-based risk assessment methods. Wang et al. (2016) determined the risk factor weights with the combined entropy and expert evaluation method, then prioritized failure modes by using the DEMATEL method, and finally designed an improved FMECA for feed system of CNC machining center.

Gandhi and Agrawal (1992) presented a method for FMEA of mechanical and hydraulic systems based on a digraph and matrix approach by considering structural and functional interaction of the system. Liu et al. (2014a) developed a novel FMEA model, which uses fuzzy digraph and matrix approach for risk evaluation and prioritization of failure modes. This model first developed a risk factor fuzzy digraph considering risk factors and their relative importance, then formed

corresponding fuzzy risk matrixes for all the failure modes in FMEA, and finally computed the risk priority indexes (RPIs) to determine the risk priority of the failure modes.

2.2.6 Hybrid MCDM Methods

Kutlu and Ekmekçioğlu (2012) considered a fuzzy approach for FMEA by applying fuzzy TOPSIS integrated with fuzzy AHP, in which the fuzzy AHP is applied to determine the weight vector of risk factors and the fuzzy TOPSIS is adopted to get the risk ranking orders of failure modes. Ekmekçioğlu and Kutlu (2012) further applied the fuzzy hybrid FMEA approach based on fuzzy TOPSIS and fuzzy AHP to a spindle manufacturing process. Liu et al. (2015e) presented a risk evaluation methodology for FMEA based on combination weighting and fuzzy VIKOR, in which integration of fuzzy AHP and entropy method is utilized for risk factor weighting and fuzzy VIKOR method is used to obtain the risk priorities of the identified failure modes. Liu et al. (2015b) combined the VIKOR, the DEMATEL, and the AHP to develop a hybrid MCDM method for FMEA, which used a modified VIKOR method to determine the effects of failure modes together and the DEMATEL technique in conjunction with AHP to construct the influential relation map among failure modes and determine the prioritization level for the failure modes.

Liu et al. (2011) reported a risk priority model using fuzzy evidential reasoning (FER) approach and grey theory to improve the effectiveness of the traditional FMEA. In this model, the FER approach was employed to capture FMEA team members' diversity opinions under different types of uncertainties, and the GRA method was used to determine the risk priorities of the failure modes that have been identified. In Du et al. (2014), the authors applied ER approach to express FMEA team members' assessment information, employed the TOPSIS to acquire the risk priority of failure modes, and finally provided a fuzzy FMEA method using the ER and the TOPSIS.

Chang et al. (2013) proposed an approach based on the GRA and the DEMATEL to rank the risk of failures in FMEA, and Chang et al. (2014) integrated the TOPSIS and the DEMATEL methods to analyze the prioritization of failure modes in FMEA.

2.3 Bibliometric Analysis

Bibliometric analysis is a pragmatic research tool used to evaluate a specific field of study. Based on all the relevant papers on FMEA improvements (165 articles), a bibliometric analysis is conducted in this chapter regarding the uncertainty theories adopted in FMEA, the quantity of articles published per year, the journals in which the articles appeared, the application areas of FMEA, the most prolific authors, and

the highly cited papers. The results obtained are shown in Figs. 2.1, 2.2, 2.3, 2.4, and 2.5 and Table 2.2. The main purpose of conducting bibliometric analysis is to provide quantitative measures of the analyzed papers. Recent tendencies, distribution of the articles with respect to different categories, and interactions with other fields can give further insights for researchers working in this field.

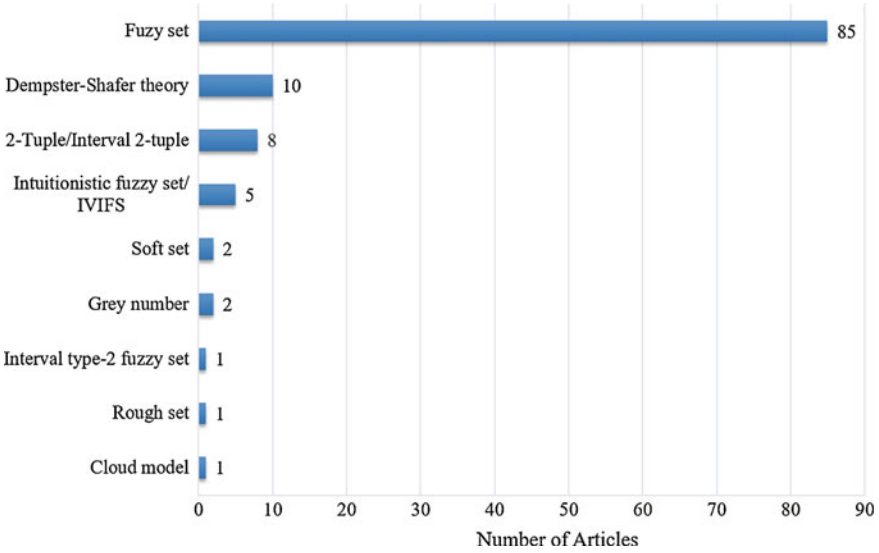


Fig. 2.1 Uncertainty theories used in the reviewed papers

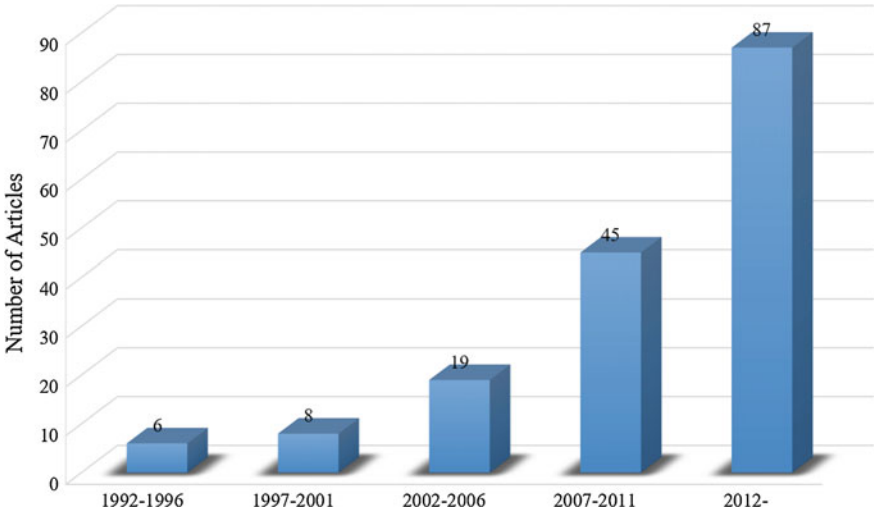


Fig. 2.2 Publishing trend on FMEA improvements

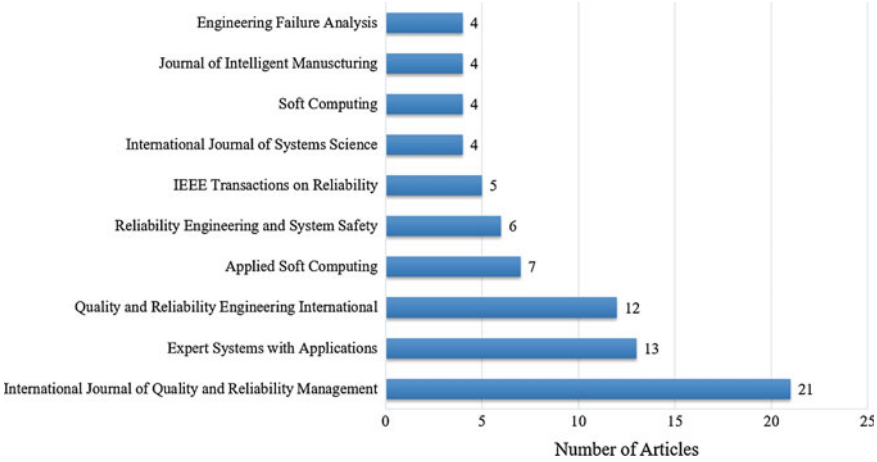


Fig. 2.3 The top ten publishing journals

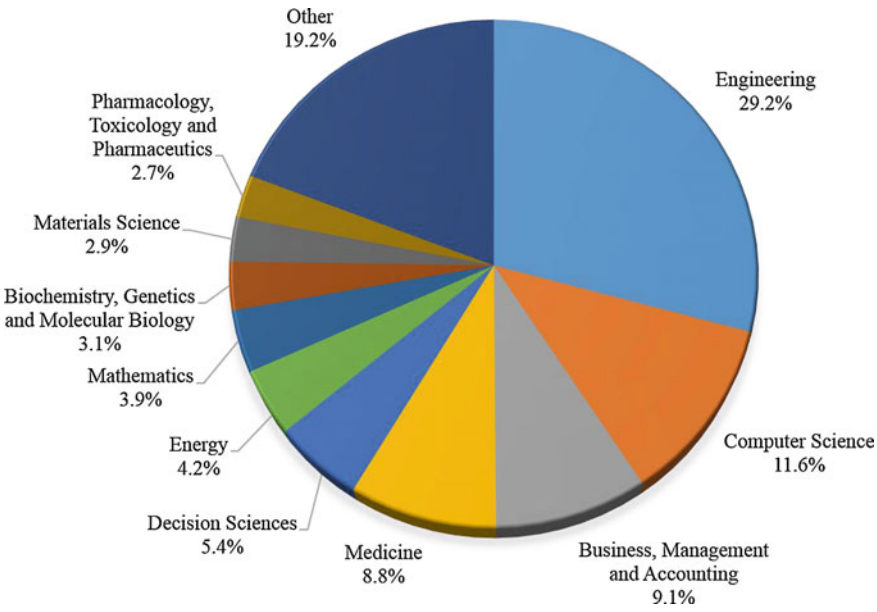


Fig. 2.4 Distribution of articles with respect to application areas

To handle the vagueness of human thought and expression in risk assessments, a lot of uncertainty theories have been used in FMEA to produce more accurate and robust results. Therefore, it is necessary to review the uncertainty theories employed in the collected papers. The number of published papers using every uncertainty method is depicted in Fig. 2.1. As it is shown in Fig. 2.1, fuzzy set is the most

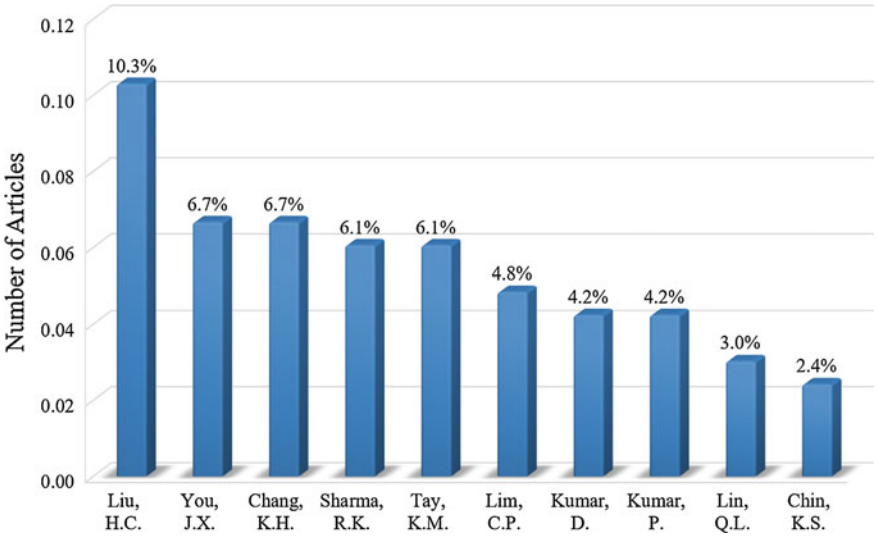


Fig. 2.5 The top ten researchers

Table 2.2 The top 10 papers based on citation measure

Reference	Average citation	Total citation
Liu et al. (2013)	32.50	65
Kutlu and Ekmekcioglu (2012)	29.33	88
Wang et al. (2009)	24.00	144
Pillay and Wang (2003)	18.50	222
Liu et al. (2012)	17.00	51
Chin et al. (2009)	16.33	98
Liu et al. (2011)	14.50	58
Seyed-Hosseini et al. (2006)	14.33	129
Xiao et al. (2011)	14.25	57
Yang et al. (2008)	13.29	93

prevalently applied uncertainty theory for dealing with the ambiguities of FMEA team members' assessments, followed by Dempster–Shafer theory, 2-tuple/interval 2-tuple, and IFS/IVIFS. Recently, the theories such as interval type-2 fuzzy set, grey number, and cloud model are also utilized by researchers to represent and handle vagueness in FMEA.

Then, from Fig. 2.2, one can observe that the number of publications on the modification of FMEA has increased considerably, especially after the year 2007. It can be expected that the studies of improving FMEA will continue to grow at an increased pace in the coming decade. In addition, these articles are mainly published on the journals such as International Journal of Quality and Reliability

Management, Expert Systems with Applications, Quality and Reliability Engineering International, Applied Soft Computing, Reliability Engineering and System Safety, IEEE Transactions on Reliability, and International Journal of Systems Science (See Fig. 2.3). From Fig. 2.4, we can see that the FMEA and its various improvements have been widely used in a variety of areas, practically in engineering (29.2 %), computer science (11.6 %), business (9.1 %), management and accounting (8.8 %), medicine (5.4 %), and decision sciences (4.2 %).

Figure 2.5 depicts the top ten researchers in this field. As one can note, the most prolific authors are Liu (10.3 %), You (6.7 %), Chang (6.7 %), Sharma (6.1 %), Tay (6.1 %), and Lim (4.8 %). In Table 2.2, the top ten papers are given by analyzing the average citation and total citation of each publication. "Average citation" or called "citation per year" is equal to the total citation divided by the number of years from publication, and "total citation" refers to the number of Scopus citations for a paper until 2015. It can be observed from Table 2.2 that the most influenced papers in this filed are Liu et al. (2013), Kutlu and Ekmekçioğlu (2012), Wang et al. (2009), Pillay and Wang (2003), and Liu et al. (2012). It may be added here that the ranking of articles based on average citation does not necessarily match the total citation ranking. For instance, the study by Pillay and Wang (2003) is ranked the fourth in accordance with the average citations, but has the highest total citation value.

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