Status of FMECA Research and Engineering Application

Ying Chen, Cui Ye, Bingdong Liu, Rui Kang
School of Reliability and Systems Engineering
Beihang University, Beijing, China
cheny@buaa.edu.cn, buaahhz@163.com, lbd1989@126.com, kangrui@buaa.edu.cn

***Abstract*—As a basic reliability analysis method, FMECA is proved to be effective and efficient to ensure the reliability of product. The aim of our work is to present the status of FMECA research and engineering application, and give engineers more experience to do this work promoting the applications of the technology. With the developing of FMECA technology, application in space, aeronautics, automotive and electronics industries becomes more and more widely.**

Firstly, FMECA military standards and automotive and electronic industries standards are introduced. There are lots of studies in FMECA. Risk analysis, computer aided analysis, failure effect analysis and timed FMECA are widely studied all over the world. In China, more attention is paid to the use of simulation tools in failure mode analysis methods.

This study shows that, Many FMECA standards follow up with the latest developments. For example, QS9000 has pointed out that risk assessment using the RPN is unreasonable. FMECA methods are constantly improving and expanding in order to meet the demand of application. However, application of FMECA method of different organization is unbalanced. Like NEC, Philips and other large international companies pay lots of attention to inter-department cooperation and the accumulation of data. FMECA plays an important role in these companies. On the contrary, FMECA in some companies is just a work, cannot integrate in design.

Keywords-FMECA; failure mechanism; standard; current research; application status

I. INTRODUCTION

Failure Mode, Effect and Criticality Analysis (FMECA) is a reliability analysis technique frequently used to enhance reliability of a product. FMECA examines the potential failure modes within a system and its equipment in design, manufacture and use process, analyses every failure mode's cause and effect, identifies potential weak links, and puts forward improvement measures and design plans, so as to improve the reliability of product.

In order to give engineers more experience to carry out FMECA and promote the applications of the technology, this paper presents the status of FMECA research and engineering application. Related standards, improved FEMCA methods and FMECA application in different areas are introduced.

II. BRIEF HISTORY OF FMECA

FMECA originated from the United States in the 1950s.Grumman Aircraft Corporation used a method called" failure mode and effect analysis" when developing primary flight control system. Although failure mode and effect analysis was hold without criticality analysis, it still achieved good results. In the mid-1960s, FMECA was officially used for the Apollo program in the USA's aerospace industry. The academic discussion on FMEA began in 1960, and the article firstly describing how to carry out FMEA was given by Coutinho in the New York academy of Sciences in 1964.In the early 1980s, FMECA entered the microelectronics industry, and the FAA also expressly required aviation system design and analysis process must be carried out with FMECA. American automotive industry began to use FMEA methods in the mid-1980s.After 1990s, FMECA has been formed a set of scientific and complete analysis method.

III. RELATED STANDARDS

FMECA standards can be divided into military and civilian standards two categories. MIL-STD-1629A[1] is a representative military FMECA standard. Automotive industry and electronics industry standards are primary in Civilian FMECA standards, such as QS9000 and IEC60812. With the development of FMECA and the broaden field of FMECA application, the medical industries also have their own FMECA norms and manuals.

A. TM5-698-4-2006

In 2006, TM 5-698-4[2], issued by the United States Department of the Army, presented equipments FMECA process for command, control, communications, computer, intelligence, surveillance and reconnaissance facilities. This manual definitely considered the failure mechanism as a column in the table.

B. QS9000-2009

QS9000-2009 manual is suitable for DFMEA (design failure mode, effect analysis) and PFMEA (process failure mode, effect analysis) implementation of automotive accessories suppliers' products. The fourth edition of the manual made some improvements compared to the third edition, for example, it did not restrict and require FMECA table format, did not recommend Risk Priority Number (RPN) for assessment of risk, and took measures to reduce RPN of certain failure mode according to the RPN threshold.

An example is given in the manual, as shown in the table 1.

TABLE I. RPN EXAMPLE

Project	Severity	Occurrence	Detection	RPN
A	9	2	5	90
B	7	4	4	112

In Table 1, RPN value of failure mode B is greater than A, but the detection of A is greater than B. If the RPN threshold is 100, which means that if a mode's RPN value is greater than the 100, measures should be taken to reduce the RPN value. Then B will be taken measures to reduce the RPN, and A is not. In order to eliminate B, analysts must spend time on reducing the probability of occurrence or detection. Whether the risk of a failure mode is very important should be determined on analysis of severity, occurrence and detection, rather than the RPN threshold. From this example, we can see its limitations.

QS9000 Manual for the fourth edition explains and contrasts failure modes, failure mechanisms and failure reasons in detail. Mentioned in the manual, all causes of potential failure modes are important to the follow-up. As for identifying potential failure modes and understanding the failure mechanisms of every failure mode should be paid more attention. What's more, the difference between failure modes and failure mechanisms should be distinguished. Failure mechanism is physical, chemical, electronic, thermal or other process leading to failure. Failure mechanisms all we can think of for every failure mode should be listed. For the system, failure mechanism is a communication process after component's failure which results in system failure. There may be several interrelated failure modes of a product, and these modes have the same failure mechanism. Ensuring failure effects analysis is an important part of the DFMEA.

C. *IEC60812-2006*

In 2006, International Electronical Commission published IEC60812-2006 FMECA standard. Compared to other previously published version, the version of the IEC made the following improvements:

- Introduced the concept of failure mode effects and criticality;
- Included a wide range of analytical methods used in automotive industry;
- Increased association with other failure mode analysis methods;
- Increased some application examples;
- Provided advantages and disadvantages of different FMEA methods.

D. *JEP 131A-2005*

In 1998, Joint Electron Device Engineering Council published 《Potential Failure Mode and Effects Analysis》, the latest version is JEP 131A -2005. This publication applies to electronic components, subassemblies product, process development, manufacturing processes and the associated performance requirements in customer applications. These areas include package design, chip design, process development, assembly, fabrication, manufacturing, materials, quality, service, and suppliers, as well as the process requirements needed for the next assembly. The purpose of this document is to establish a minimum guideline for the application of FMEA techniques to improve quality, reliability, and consistency of electronic components subassemblies by continually evaluating the product or process against potential failure modes. OEMs must provide suppliers with their manufacturing processes, their use conditions on the failed parts, and their failure experiences. Suppliers must seek continuous improvement and have the responsibility of developing and improving the elements of FMEA.

IV. RELATED RESEARCH

In recent years, international scholars have studied a lot of ways to improve the FMECA. These methods are mainly concentrated in four areas.

A. *Multiple failure mode effect analysis methods*

Krasich mentions that FMEA treats each failure mode as independent, and the failure modes listed in FMEA cannot cover all of the product failure modes, so FMEA will not guarantee that the product does satisfy the reliability requirements [12]. To improve FMECA only with single failure mode analysis, FMECA model for multiple failures is proposed, extending the use of FMECA.

Christopher uses AutoSteve to simulate the behavior of the circuit under component failures, which contains multiple failure modes and effects analysis, using a weighted evaluation to synthesize the impact of multiple failure modes [13].

Pickard [14] proposes an approach to multiple failures of complex system. On the basis of this work, Xiao [15] proposes a minimum cut set based method for assessing the impact of multiple failure modes. C. J. Price[16] presents a weighted evaluation method to synthesize the impact of multiple failure modes.

B. *Risk analysis method*

John [20] points out the defects of the traditional methods of risk analysis--Risk Priority Number methodology:

- The same number can (in general) be constructed from many different combinations of the severity, occurrence, and detection rankings.
- The RPN scale is not continuous, only 120 of the 1000 numbers generated from the product of S, O, and D are unique.
- In general each of the rankings can be formed in several different ways. It is difficult to accept that failures having

different severity can be evaluated as having the same importance.

- These three parameters are handled with simple multiplication, which can not reflect their specific contributions to RPN. Contributions to risk of these three evaluation objects are different for different systems.
- Minor changes in one of these three factors have different effects on the RPN
- Comparing multiple parameters should be implemented instead of comparing the two RPN, which doesn't correctly reflect the degree of importance of fault. E.g., RPN1 < RPN2 if S1 < S2, O1 < O2, and D1< D2)

It can be seen that traditional RPN risk quantitative analysis is not very objective and rigorous. To solve these problems, researchers put forward three different approaches. Include: Improved RPN probabilistic risk analysis methods, fuzzy risk analysis method and Risk Analysis considering the cost of failure. Meanwhile, according to the results of these studies, corresponding standards have also been adjusted. For example, RPN is not recommended as a basis for improved design in the fourth edition of QS9000 manual.

1) Improved RPN probabilistic risk analysis methods

John [20] proposes the detection ranking should be dropped, because of the detection having minor importance for the distinction between the degree of harm, and the rankings for the severity categories should also be scrapped. In addition, he also suggests the product of the cost of the failure effect and the probability of occurrence of the potential failure mode should be the evaluation criteria.

Bevilacqua [21] thinks that the RPN consists 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). Sankar and Prabhu[22] describe a new technique for prioritizing failures for corrective actions in FMEA. The ranks 1 through 1000 are used to represent the increasing risk of 1000 possible severity-occurrence-detection combinations, called risk priority ranks (RPRs). The failures having higher ranks are given higher priority. Braglia [23] and Kara-Zaitri [24] also propose corresponding methods.

Currently, researchers have different opinions in weighting hazard factors. For example, Pillay and Wang [25] think the order of factors importance is D, S and O, but Braglia [26] is aware that the harm of a failure mode with very high severity and very low probability of occurrence is much less than the harm of a repeated failure mode.

2) Fuzzy risk analysis methods

Though RPN has provided quantitative method for risk assessment, there exists fuzziness in the process from data collecting to result calculating, because of the widespread staffs involved in risk data collecting and the difference in data providing staffs' areas, departments, jobs and opinions. For example, when evaluating failure effects, it is difficult to give an only value because a failure mode may bring effects in different degree, and that different person has different evaluation. You can value it 7, 8, or 9. When giving a definite value at the request of risk priority number, no matter the score is 7, 8, or 9, the other two scores' fuzzy information will lost.

We can use fuzzy mathematical analysis method to solve this problem in the use of traditional FMECA. For example, we change risk data from definite sets to relevant fuzzy sets, and carry out weighted analysis of the contribution to severity, occurrence, and detection of risk. Risk analysis method built on fuzzy logic is also called fuzzy risk analysis.

Research on fuzzy risk analysis is very wide all over the world, Braglia[26] proposes an alternative multi-attribute decision-making approach for prioritizing failures in FMECA, based on a fuzzy version of the 'technique for order preference by similarity to ideal solution' (TOPSIS). Chang [27][28] uses grey theory, namely fuzzy linguistics, for example, he uses Very Low, Low, Moderate, High, and Very High to evaluate OSD degree, and uses grey relation analysis to determine the priority of potential reasons. Bowles [29] proposes a new technique, which uses the linguistic terms to describe the riskiness of OSD and failures based on fuzzy logic, for prioritizing failures for corrective actions in system FMECA. Relation between riskiness and OSD is usually described by fuzzy 'If-Then' rule, and both degree and OSD are fuzzified. Yang [30] proposes a fuzzy rule-based Bayesian reasoning approach for prioritization of failures in FMEA at the aim of improving some disadvantages in traditional fuzzy logic used in FMEA.

Garcia[31], Zafiropoulos[32], Pelaez[33], Pinay[34], Gareia[35], Sharma[36] all propose their own methods. And these methods are applied in electronic products such as switch power.

3) Cost-Based FMEA

To solve the problems of RPN method, the cost of failure is proposed as a way to assess failure mode and effect or risk. In terms of the management, linking cost to reliability improvements is favorable to balance them in the case of a limited budget and allow better distribution of resources. Von Ashen[41] proposes a Cost -oriented FMEA, applied to operation of vehicle air conditioning and engine cooling operation control unit. Rhee[42] proposes an approach "life cost-based FMEA", which measures risk in terms of cost. Life Cost-Based FMEA is useful for comparing and selecting design alternatives that can reduce the overall life cycle cost of a particular system. Stanford SLAC National Accelerator Laboratory carries out a cost-based FMEA supported by the U.S. Department of Energy, and provides Manual for Life Cost Based FMEA.

Cost-based methods of risk analysis also have shortcomings, for example, real cost of failure mode must be estimated, additional management models are included to support the calculation for cost information, etc.

C. Computer-Aided FMECA

Carrying on FMEA needs to create tables and fill in large amounts of data, consuming time and energy. Boeing can be considered as the earliest organization to implement FMEA, having a lot experience in applying this method. The evaluation of FMEA given by technicians in Boeing is "The principles of

FMEA are straightforward and easy to grasp. The practice of FMEA is tedious, time consuming, and very profitable."[47] This shows that it's considerably labor-intensive to do a good FMEA job. The emergence of computer-aided FMECA is trying to extricate analysts from the workload, improve the efficiency of analysis, and avoid omissions in manual analysis. Kukkal[48] and Bowles[49] describe the establishment of database-assisted FMEA works. Currently, Managers in Hong Kong and technicians in mainland China factory can use a common FMEA analysis platform on the Internet, and all data are stored in network servers [51].

D. *Intelligent FMECA*

Three ways can be used to achieve Intelligent FMECA reasoning analysis: numerical simulation, expert systems and causal reasoning. Numerical simulation method is the first kind intelligent FMEA method, using fault injection to simulate components of fault status. Since the input information of the simulation is usually not accurate, in order to improve simulation accuracy, we should increase computation to the search for reasonable values. When using knowledge related to expert systems to infer how component failure modes affect the whole system, we need to get a lot of information on failure modes and effects, and clear the relationship among these effects spreading to system input or output.

Teoh[53] proposes a FMEA approach generated by knowledge modeling in the conceptual design stage. Henry [54] uses a Markov model to trace fault. Catherine [55] generates a reliability model reasoning from structural and functional system design specifications, defining system state space to characterize the effects of single and multiple component failures. Applying blackboard model, Russomann[57] designs expert system to assist in performing FMECA, which can serve as the foundation for further research into automating the FMEA process. Daniel, in Martin Marietta Airline Company, integrates CAD/CAE (computer-aided design and engineering) platforms into a kit, to automate the FMECA process. David [60] presents an Automated FMEA approach depending on the qualitative circuit analysis. Pelaez[61] applies Fuzzy Cognitive-Maps knowledge-Representation to complete the reasoning process of FMEA. Ku [62] uses a series of back-Propagation neural networks (BPNs) to form a hierarchical framework adequate for the implementation of an intelligent FMEA.

E. *Timed FMECA*

Traditional FMEA cannot detect faults associated with the time. Aim at this limitation, Robert Colvin proposed a new FMEA approach-- timed FMEA. Bondavalli and Simoncini hold the view that time-related failures accounted for 2 / 5 in failures leading to harmful behavior. They confirm specific component failure modes affecting on normal operation of the system through fault injection, continue to repair timed Behavior Trees model, so as to achieve dynamic analysis.

V. FMECA ENGINEERING APPLICATION

A. *Aerospace*

In 1991, Roma Reliability Analysis Center collected a large number of failure modes and mechanisms data, to Support FMECA [109] .

NASA takes FMEA as the main risk assessment tool, having evaluated several projects. For example, anti coincidence detector installed in high-power GLAS gamma ray telescope is analyzed; failure modes, such as high wheel speed and Sensor redundancy, are positioned in the FMECA analysis of wind turbines. These are improved in early design stage.

DARPA develops software MOVAT in MoBIES project, including hardware and software FMEA modules to analyze in the demand and follow-up stages.

Boeing developed the FMEA / FMECA process manual, and actively promoted FMEA in implementation of projects. For example, in C-17 Single Line project, Boeing used FMEA risk assessment methods in C-17 Cargo aircraft manufacturing and assembly process [111].

James Carlin Becker [96] in Lockheed Martin carried on FMECA in distributed computing system for air traffic control. Critical failure modes in analysis results have been experimental verified.

European space agency planed to develop automated FMECA software for European Plan 10(GRD1-2001-40133) in AUTAS project [112]. The software was finished in 2004, and put into use in IAI, Alenia and Eurocopter [113].

B. *Automotive industry*

Ford Motor Company introduced FMEA in 1972, and required all its suppliers to provide detailed FMEA, Including the reports of design stage and process stage. This method was accepted and successfully used in the automotive industry until 1990s, required by a series of industry standards and certification requirements.

In the early 1990s, Aldridge conducted an investigation of the status of FMECA application in Garrett Automotive Ltd. It was pointed out that FMEAs had mainly been primarily used to satisfy the demands of major customers, with inconspicuous effects. GAL took various measures to solve the application of FMEA, including establishing FMEA teams from the management level to make the various departments involved in the analysis process, collecting feedback from the users and building database to support FMEA. These measures had achieved some satisfactory results to the end of the investigation.

During the same period, 78 UK automotive industry research firms or sectors showed [119] that the majority of suppliers only started to use FMEA because it was a contractual requirement of their customer; however, a number of them are now seeking to make more use of the technique to facilitate their process of quality improvement; FMEA was treated by the majority of organizations as a team activity; engineers still viewed FMEA as a hard slog. more use should be made with computerized aids to reduce the effort in preparing and updating the FMEA; and the main difficulties encountered in the use of FMEA were related to time constraints, poor organizational understanding of the importance of FMEA, inadequate training and lack of management commitment.

Onodera investigated about 100 FMEA applications in the mid-1990s, revealing that the FMEA technique was successfully applied in Japan's automotive, electronics, consumer goods, energy electricity and wireless communications.

In 2011, Neagoe firstly summarizes the development process of FMEA in the automotive industry in Reference [121]. As an engineer in automotive industry, Neagoe pointed out the shortcomings of traditional FMEA, and presented several research opportunities, including: Computer-aided FMEA, cost-based FMEA and FMEA information management. In his view, these methods can be used to solve some problems in application from a technical point of view.

C. Semiconductor Industry

FMEA application in the semiconductor industry began to rise from 1990s. As suppliers for Ford Motor Company, Texas Instruments Inc. and Intel Corporation carried out a lot of FMEA training[122]. Some Semiconductor Enterprises developed their own FMEA implementation guides [123].

Whitcomb[104] introduced FMEA deployment in a Semiconductor Manufacturing Environment of National Semiconductor fab. Design of Oxide thin-film deposition process was unreasonable, found from analysis in LPCVD process with HCMOS logic devices. Through the improvement process RPN score decreased from 180 to 60.

Japan's semiconductor manufacturing industry began to use FMEA to improve reliability in 1980s. In NEC, FMEA became the most important method to improve the reliability of the process of developing new product. In 1990s, FMEA became one of NEC design standards. FMEA allowed the accumulation of NEC's design experience to prevent the occurrence of former failures in the development of new products.

D. Other industries

In 2001, U.S. health care organizations adopted a standard, providing managers in health care organizations must implement FMEA at least one time a year. ICU (intensive care unit) was the earliest department to use FMEA. In order to smoothly promote FMEA in health care system, a lot of training was developed.

Philips is one of the leading companies, having variety of product. Figure 1 is a schematic implementation of FMEA in Philips. From the figure we can see, FMEA has been integrated into the corporate R & D process, and bring the strength of the various departments together. Philips has developed FMEA tools. Computer-aided measures were used to fill out forms and generate records in FMEA implementation process. The company also established a FMEA database, and set up a special team to maintain database. Designers also drew support from FMEA database to look for better design solutions in the development process.

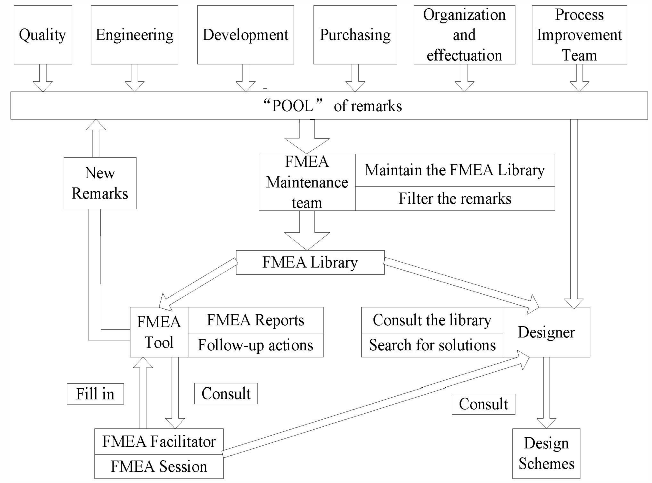

Figure 1. FMEA schematic implementation in Philips.

VI. FMECA IN CHINA

In the early 1980s, the concepts and methods of FMECA were gradually adopted in China, reflecting in related standards establishing, methods' studying and applying and other aspects.

A. Related FMECA standards

In 1992, national military standard, GJB1391-92 "Procedure for failure modes, effects and criticality analysis" was issued, applied to the developing, producing and service stages but inapplicable to software. This standard is the most widely referred to and used standard in China. In 1996, GJB1391-92 was replaced by GJB/Z1391-2006 "Guide to failure modes, effects and criticality analysis". The later one is applicable to the whole stage in the product life circle. Process FMECA, Software FMECA and a large number of cases are added.

In 1995, aviation standard HB/Z281-95 "Guide to failure modes, effects and criticality analysis of aviation engine" was issued by Aviation Industry, applied to the developing, producing and service stages of aviation engine structure but inapplicable to software. The standard provides a large quantity of failure modes information of aviation engine products.

FMECA standards of aerospace industry include: QJ 3050-1998 "Guide to failure modes, effects and criticality analysis of aerospace production" [10], QJ 2437-1993 "Failure modes, effects and criticality analysis of satellites" [11], etc.

B. Study of FMECA methods

In China, basic theories of FMECA mainly include fuzzy risk analysis method and intelligent FMECA. In 1980s, Tianxiang Zeng [73] considered the failure modes, effects and fuzzy risk calculation methods, and developed computer aided analysis program for huge failure modes, effects and fuzzy risk analysis database system. Fuzzy lethality degree analysis method in matrix FMECA considered by Luyue Ju[76], can track and calculate failure modes and effects from components to system in complex systems, which economizes manpower, material resources and time. In addition, Ying An[77], Kai Xu

[78] and Qirui Tan [81] conduct a lot of research in fuzzy risk analysis. Yi Yang [83] rises up a new progress FMECA method, which is a cost judgment criteria based on probability.

Bin Wang [85] rises up a failure risk estimate and optimization approach mechanical production design scheme, which is based on knowledge model, and deduces a new RPN calculation method. Ming Cheng [86] applies failure mechanism model to FMECA in huge complex systems. Tingdi Zhao [87] integrates neural network, expert system, and traditional analysis technology to FMECA technology, and sets up intelligent FMECA reasoning model, so as to achieve maximizing automaticity of FMECA.

C. Status of FMECA engineering application

In the application of FMECA, China pays more attention to the combination of reliability, safety, maintainability, supportability and PHM, etc. In the reliability research of plane landing system, Yue Sun [88] combines FMECA, FTA, and FRACAS, so as to make full use of information flow, combine analysis and design effectively, form the closed loop quality management system, and achieve zero failure. Hai Zhang [89] takes use of FMEA based on the function role model, does analysis in terms of function design, and proves the method is applicable to the testability BIT design. Chuanfu Gan[90] considers that in some type of radar integrated support work, we can meet integrated support design requirements through developing FMECA work. Yuwei Yang[93] carries on FMEA to engine, analyzes the crack failure mode of the motor high pressure turbine blade, and provides a basis for realizing the integration diagnosis of engine wear fault.

In addition, in China, FMECA method has been widely used in transport aircrafts, helicopters, spacecraft assembly, space launch site, satellite, space-borne computer, aviation engine, clutch servo system, radar and CNC processing system for every area in both military and civilian, providing guarantees for the reliability design of products.

VII. SUMMARY

From what we have talked above, the status of FMECA research and engineering application can be summarized as follows:

- Many studies are done to find shortcomings of traditional FMECA. In order to overcome these disadvantages and meet the requirements of application, lots of improved methods are proposed. For example, to improve FMECA only with single failure mode analysis, FMECA model for multiple failures is proposed. To extricate analysts from the workload, improve the efficiency of analysis, and avoid omissions in manual analysis, computer-aided FMECA methods are widely studied.
- Many FMECA standards follow up with the latest developments. For example, QS9000 has pointed out that risk assessment using the RPN is unreasonable.
- Application of FMECA method of different organization is unbalanced. The use of FMECA is very wide in aerospace, while it has experienced a process from being known to being accepted in automotive industry. Large international companies, like NEC and Philips, pay lots of attention to inter-department cooperation and the accumulation of data. FMECA plays an important role in these companies. On the contrary, FMECA in some companies is just a work, cannot integrate in design.

In order to perform a thorough FMECA, a lot of measures should be taken, such as, building databases, collecting failure data and using simulation methods to assist the analysis of failure mechanism. More training should be offered to engineers so that they can understand FMECA more deeply. During FMECA, different department should be involved, such as design, process, test, management department. FMECA working in team and the whole manufacture process FMECA are effective means to improve design of reliability.

REFERENCES

[1] MIL-STD 1629 “Procedures for performing a failure mode and effect analysis”

[2] TM 5-698-4 “Department of the Army, Failure Modes, Effects and Criticality Analyses (FMECA) for Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) Facilities,” 29 September 2006

[3] ECSS-Q-30-02A “Space product assurance ”

[4] “Porential failure mode and effects analysis (FMEA) Reference Manual. Fourth Edition.” June 2008.Chrysler LLC, Ford Motor Company, General Motors Corporation.

[5] SAE J1739-2009 “Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)”

[6] IEC 60812 “Procedures for failure mode and effect analysis(FMEA)”

[7] JEP 131A (2005-05) JEDEC “Potential Failure Mode and Effects Analysis (FMEA)”

[8] BS 5760 Reliability of Constructed or Manufactured Products, System, Equipments and Components Part 5, “Reliability of systems, equipment and components. Guide to failure modes, effects and criticality analysis (FMEA and FMECA)”, 1991

[9] GJB/Z1391-2006 “Guide to failure mode, effects and criticality analysis”

[10] QJ 3050-1998 “Guide to failure modes, effects and criticality analysis of aerospace production”

[11] QJ 2437-1993 “Failure modes, effects and criticality analysis of satellites”

[12] M. Krasich. “Can Failure Modes and Effects Analysis Assure a Reliable Product,” Reliability and maintainability symposium,2007:277-281

[13] C. J. Price, N. S. Taylor. “FMEA For Multiple Failures,” Reliability and Maintainability Symposium. 1998, pp. 43-47.

[14] K. Pickard, P. Muller, B. Bertsche. “Multiple failure mode and effects analysis: an approach to risk assessment of multiple failures with FMEA.” Reliability and maintainability symposium, 2005. Annual, Piscataway: Institute of Electrical and Electronics Engineers Inc; 2005, pp. 457–62.

[15] Ningcong Xiao, Hongzhong Huang, Yanfeng Li, Liping He, Tongdan Jin. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. Engineering Failure Analysis 2011(18): 1162–1170.

[16] C. J. Price, N. S. Taylor. Automated multiple failure FMEA. Reliability Engineering and System Safety. 2002, (76):1-10.

[17] D. Cayrac, D. Dubois, M. Haziza, H. Prade. Possibility Theory in “Fault Mode Effect Analyses” - A Satellite Fault Diagnosis Application

[18] D. He, A. Adamyan. “An impact analysis methodology for design of products and processes for reliability and quality,” Proceedings of ASME Design Engineering Technical Conference, Pittsburgh, PA;2001.

[19] B. Lee. "Using Bayes belief networks in industrial FMEA modeling and analysis," Proceedings of International Symposium on Product Quality and Integrity, Philadelphia, PA; 2000.

[20] B. B. John. An Assessment of RPN Prioritization in a Failure Modes Effects and Criticality Analysis(IEEE)

[21] M. Bevilacqua, M. Braglia, R. Gabbrielli. Monte Carlo simulation approach for a modified FMECA in a power plant, Quality and Reliability Engineering International. 2000,(16):313–324

[22] N. R. Sankar, B. S. Prabhu, Modified approach for prioritization of failures in a system failure mode and effects analysis, International Journal of Quality & Reliability Management2001, 18 (3): 324–335.

[23] M. Braglia, MAFMA: multi-attribute failure mode analysis, International Journal of Quality & Reliability Management 2000, 17 (9): 1017–1033.

[24] C. Kara-zaitri, A. Z. Keller, I. Barody. "An improved FMEA methodology," IEEE Proceeding Annual Reliability and Maintenance Symposium, 1991, pp.248-252.

[25] A. Pillay, J. Wang. Modified failure mode and effects analysis using approximate reasoning, Reliability Engineering & System Safety. 2003,(79): 69–85

[26] M. Braglia, M. Frosolini, R. Montanari. Fuzzy TOPSIS approach for failure mode, effects and criticality analysis, Quality and Reliability Engineering International. 2003, (19): 425–443.

[27] C. L. Chang, C. C. Wei, Y.H. Lee, Failure mode and effects analysis using fuzzy method and grey theory, Kybernetes. 1999, (28):1072–1080.

[28] C. L. Chang, P. H. Liu, C. C. Wei, Failure mode and effects analysis using grey theory, Integrated Manufacturing Systems.2001,12 (3):211–216.

[29] J. B. Bowles, C. E. Peláez. Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis, Reliability Engineering and System Safety. 1995(50): 203–213.

[30] Z. Yang, S. Bonsall, J. Wang, Fuzzy rule-based Bayesian reasoning approach for prioritization of failures in FMEA, IEEE Transactions on Reliability. 2008, 57 (3):517–528.

[31] M. Braglia, M. Frosolini, R. Montanari. Fuzzy criticality assessment model for failure modes and effects analysis, International Journal of Quality & Reliability Management 2003, 20 (4):503–524.

[32] E. P. Zafiropoulos,E. N. Dialynas. Reliability prediction and failure mode effects and criticality analysis (FMECA) of electronic devices using fuzzy logic. International Journal of Quality & Reliability Management.2005, 22(2):183-200.

[33] C. E. Pelaez, J. B. Bowles. "Applying fuzzy cognitive-maps knowledge-representation to failure mode effects analysis," IEEE Proceeding Annual. Reliability and Maintenance Symposium, 1995, pp. 450-456.

[34] A. Pillay, J. Wang. Modified failure mode and effects analysis using approximate reasoning. Reliability Engineering and System Safety, 2003, 79(1):69-85.

[35] P. A. Garcia, R. Schirru, P. F. Frutuoso. A fuzzy data envelopment analysis approach for FMEA. Progress in Nuclear Energy, 2005, 46(3-4):359-373.

[36] E. P. Zafiropoulos, E. N. Dialynas. Reliability prediction and failure mode effects and criticality analysis (FMECA) of electronic devices using fuzzy logic. International Journal of Quality &Reliability Management. 2005, 22(2):183-200.

[37] K. M. Tay. "On Fuzzy inference system based Failure Mode and Effect Analysis (FMEA) methodology," international conference of soft computing and pattern recognition.2009, pp.329-334.

[38] R. K. Sharma, D. Kumar, P. Kumar. Systematic failure mode effect analysis (FMEA) using fuzzy linguistic modelling. International Journal of Quality & Reliability Management. 2005,22(9):986-1004

[39] K. S. China, Y. M. Wang, G. K. Poona, J. Yang. Failure mode and effects analysis using a group-based evidential reasoning approach. Computers and Operations Research. 2009(36):1768-1779.

[40] H. C. Liu, L. Liu, Q. H. Bian, Q. L. Lin. Failure mode and effects analysis using fuzzy evidential reasoning approach and grey theory. Expert Systems with Applications. 2011(38): 4403–4415

[41] V. Ahsen, Cost-oriented failure mode and effects analysis, International Journal of Quality & Reliability Management. 2008, 25(5): 466–476.

[42] S. J. Rhee, I. Kousuke. Using cost based FMEA to enhance reliability and serviceability. Advanced Engineering Informatics. 2003, 17(3-4):179-188.

[43] Life Cost Based FMEA Manual. A step by step guide to carrying out a cost based Failure Modes and Effects Analysis

[44] Tarum CD. FMERA—failure modes, effects, and (financial) risk analysis. SAE World Congress, Detroit, MI; 2001.

[45] W. Gilchrist. Modeling failure modes and effects analysis. Quality Reliability Manage. 1992(10):16–23.

[46] S. J. Rhee, K. Ishii. Using cost based FMEA to enhance reliability and serviceability. Advanced Engineering Informatics. 2003(17): 179–188.

[47] www.ferp.ucsd.edu/ARIES/MEETINGS/1104/Weaver.ppt

[48] P. Kukkal. "Database Design for Failure Modes and Effects Analysis Annual," Reliability and Maintainability Symposium.1993, pp.231-238.

[49] J. B. Bowles, C. E. Pelaez. Fuzzy logic prioritization of failures in a system failure mode effects and criticality analysis. Reliability Engineering and System Safety, 1995, 50(2):203-213.

[50] Multi signal Modeling for Diagnosis, FMECA, and Reliability (IEEE)

[51] G. Q. Huang, M. Nie, K. L. Mak. Web-based failure mode and effect analysis (FMEA). Computers & Industrial Engineering. 1999(37): 177-180.

[52] P. Luthra , Electronics & Space Corp. ,St. Louis FMECA: An Integrated Approach (IEEE)

[53] P. C. Teoh, K. Case. Failure modes and effects analysis through knowledge modeling. Journal of Materials Processing Technology. 2004(153–154): 253–260 (Elsevier SciVerse SD).

[54] O. Henry, B. William, H. Roger. Statistical Model for a Failure Mode and Effects Analysis and its Application to Computer Fault-Tracing.1978, 27(2):16-22.

[55] M. M. Catherine. Reliability model generator for fault-tolerant systems (AIAA)

[56] X. G. An, H. Hecht. Better V&V for Critical Flight Systems (AIAA)

[57] D. J. Russomanno, R. D. Bonnell, "Bowles J B. A blackboard model of an expert system for failure mode and effects analysis," IEEE Proceeding Annual Reliability and Maintenance Symposium, 1992, pp.483-490.

[58] D. Bell, L. Cox. "Using causal reasoning for automated failure modes and effects Analysis (FMECA)," Proceedings Annual reliability and maintainability symposium.1992, pp. 343-354.

[59] D. Palumbo, "Automating Failure Modes And Effects Analysis," Proceedings Annual reliability and maintainability symposium.1994, pp. 304-309.

[60] R. P. David. "Dynamic Analysis of Qualitative Circuits for Failure Mode and Effects Analysis," Proceedings Annual reliability and maintainability symposium.1996, pp.37-42.

[61] C. E. Pelaez. "Applying Fuzzy Cognitive-Maps Knowledge-Representation to Failure Modes Effects Analysis," Proceedings Annual reliability and maintainability symposium.1995, pp. 450-456.

[62] C. Ku, Y. S. Chen, Y. K. Chung. "An Intelligent FMEA System Implemented with a Hierarchy of Back-Propagation Neural Networks," IEEE Conference on Cybernetics and Intelligent Systems.2008, pp. 203-208.

[63] D. J. Russomanno. "Functional Reasoning in a Failure Modes and Effects Analysis (FMEA) Expert System," Annual reliability and maintainability symposium.1993, pp. 339-348.

[64] J. R.David. "A Blackboard Model of an Expert System for Failure Mode and Effects Analysis," Annual reliability and maintainability symposium.1992, pp.483-490.

[65] C. J. Price. "The Flame System: Automating Electrical Failure Mode & Effects Analysis (FMEA)," Proceedings Annual reliability and maintainability symposium.1995, pp. 90-96.

[66] P. Yiannis, P. David, G. Christian. "Automating the Failure Modes and Effects Analysis of Safety Critical Systems," Proceedings of the Eighth

IEEE International Symposium on High Assurance Systems Engineering (HASE04).2004

[67] M. Lehtela, "Computer-Aided FMEA of ElectronicCircuits", Microelectronics and Reliability, 1990,30(4):761-773

[68] C. J. Price, N. S. Taylor, "Automated multiple failure FMEA", Reliability Engineering and System Safety, 2002(76):1-10.

[69] E. Jonas, S. Nadjm-Tehrani. "Tool Support for Incremental Failure Mode and Effects Analysis of Component-Based Systems," Reliability and Maintainability Symposium, 2007, pp. 277-281.

[70] P. G. Hawkins, D. J.Woolons. Failure modes and effects analysis of complex engineering systems using functional models [J]. Artificial Intelligence in Engineering 1998,12(4): 375-397

[71] R. Colvin, L. Grunske, K. Winter. Timed Behavior Trees for Failure Mode and Effects Analysis of time-critical systems. The Journal of Systems and Software. 2008(81): 2163–2182

[72] J. B. Wang, D. R. Yu. Real-time simulation of leak fault of liquid rocket engine. Journal of propulsion technology.1999,20(5) :1-6

[73] J. Y. Tang, Y. X. Zhao. FMECA Modeling Method Based on Transfer Matrixing. Railway Locomotive & Car.2008,28(4):54-58

[74] T. X. Zeng. Failure mode, effects and lethality analysis. Research report of avaition intelligence, 1985.

[75] L. Y. Ju. Failure mode, effect and fuzzy risk analysis and its program of computer comp. Journal of Shanghai University(natural science) 1999,5(2):138-143

[76] L. Y. Ju. Fuzzy Criticality Analysis and Its Application at Matrix FMECA.Journal of Shanghai University(natural science).1999, 5(5):463-466.

[77] Y. An, C. X. Song, Y. S. Zhou. Application of FMECA in CVT reliability analysis based on fuzzy evaluation method, 2009.

[78] K. Xu, M. L. Zhu, B. Li. FMECA of Engine system based on fuzzy reasoning. Science and technology of internal combustion engine, 1999.

[79] Z. Zhou, D. Z. Ma, X. Y. Yu. Application of fuzzy FMECA in analysis of product reliability. Electric machines and control. 2010,14(10):88-93

[80] L. Wen. Fuzzy comprehensive evaluation method and AHP anaylsis method used in fault evaluation of spacecraft. Spacecraft environment engineering 2005,22(3):177-184.

[81] Q. R. Tan, S. D. Wei, K. Shi. Application study on Fuzzy FMECA in engine inner fire safety assessment of the disposal .Science and technology information. 2010.

[82] T. Liu, Z. J. Cai. Accessory safety assessment of airplane start-up electromagnetic valve based on FMECA and fuzzy comprehensive evaluation methods. Machinery. 2009(12):65-68.

[83] Y. Yang, Z. C. Yang, G. B. Chen. Study on Process FMEA and a new evaluation criteria. Quality and Reliability. 2006(6): 9-13.

[84] Z. Y. Zeng, Y. H. Li.Integrated design FMECA and PDM. Quality and Reliability. 2008(6): 22-26

[85] B. Wang, X. Q. Tang. Evaluating failure risk for product design scheme based on knowledge model. Journal of Beihang University.2008,34(7):763-768

[86] M. Chen, G. H. Wang, Y. Chen. FMEA of Large- scale Complex Products with Failure Mechanism Model. Mechatronics. 2006,12(2):40-43.

[87] T. D. Zhao. FMEA expert systems. Journal of Beihang University 1999,25(5): 611-614

[88] Y. Sun. Study on reliability of UAV landing system based on FMECA and FTA. Master's thesis University of electronic science and technology, 2010

[89] H. Zhang, J. Qiu, Y. L. Qian. Fault Analysis in the Fuel-metering System of Plane Engine. Aviation metrology & measurement technology. 2003,23(3):9-13.

[90] C. F. Gan, X. D. Liu. Development and Use of FMECA in Radar Integrated Support. .Modern radar.2006,28(4):1-4.

[91] C. F. Gan, G. Lin, Z. X. Niu. Study on Method to Developing Reliability, Maintainability and FMECA in Large Equipment. Modern Radar. 2008,30(7):33-35.

[92] K. Cicek, H. H. Turan. "Risk-Based Preventive Maintenance Planning using Failure Mode and Effect Analysis (FMEA) for Marine Engine Systems," Engineering Systems Management and its Applications, 2010,pp.1-6

[93] Y. W. Yang.Research on key intelligent diagnosis technology and failure analysis of aero gas turbine engine .Nanjing University of Aeronautics & Astronautics, 2007

[94] D. B. Todd, C. S. David. Prognostic Health Management of Aircraft Power Generators. IEEE Transactions on Aerospace and Electronic Systems. 2009,45(2):473-483

[95] G. J. Kacprzynski, M. J. Roemer, "Extending FMECA - Health Management Design Optimization for Aerospace Applications," Aerospace Conference ,2001(6):3105-3112

[96] C. B. James, G. Flick. "A Practical approach to failure mode, effects and criticality analysis(FMECA) for computing systems," IEEE Proceedings of High-Assurance Systems Engineering Workshop, Niagara Canada. 1996,pp. 228-236

[97] Q. Zuo, B. F. Wang, J. B. Hu. Application of FMECA in Process Aircraft Systems Manufacture. Aviation engineering & maintenance ,2007.

[98] W. M. Yi, G. Sun, H. Y. Liu. Reliability of Spacecraft Assembly. Spacecraft environment engineering .2006,23(3):161-165.

[99] J. Y. Wang, Y. Rao, Z. Z. Sun. FMEA System FMEA Based on Flying Event of CE-1 Orbiter. Spacecraft Engineering .2008,17(2):90-93.

[100] H. Yang, Q. Liu, X. F. Zhou. Application of reliability technique in on-board computer. Application of Electronic techinique. 2009,35(7):75-80.

[101] G. B. Hu. The Scene Analysis And The Countermeasures Of The Failure Mode For Large-Scale Marine DC Motor. CHUANDIAN JISHU. 2001, 21(1):29-35.

[102] G. Chandler, K. D. William. RAC FMD-91, Failure mode/mechanism distributions. 1991. Rome RAC

[103] W. C. Chen, S. W. Zhang. Failure Mode Effect and Criticality Analysis for Whole Tactical Missile Aerospace Shanghai.2005(1):55-62

[104] R. Whitcomb, M. Rioux .Failure Modes and Effects Analysis (FMEA) System Deployment in a Semiconductor Manufacturing Environment.IEE USEMI Advanced Semiconductor Manufacturing Conference.1994

[105] W. E. Klein, V. R. Lali. "Model-OA Wind Turbine Generator: Failure Modes & Effects Analysis," Reliability and Maintainability Symposium. 1990,pp.337-340

[106] H. Arabian-Hoseynabadi, P. J. Tavner.Failure Modes and Effects Analysis (FMEA) for wind turbines. Electrical Power and Energy Systems .2010(32): 817–824.

[107] H. Sun. FMECA & the research of radar design's quality. Electronic product reliability and environmental testing.2005,22(1):5-9.

[108] H. X. Gao, J. Li. Reliability Growth of Mobile Radar Based on FMECA. Electronic product reliability and environmental testing .2006 ,24(1):55-59.

[109] G. Chandler, W. K. Denson. RAC FMD-91, Failure mode/mechanism distributions. 1991. Rome RAC

[110] C. Moore., Failure Modes and Effects Analyses (FMEA) and Critical Items List (CIL) for the ECS Project; EOSDIS Core System Project; Hughes Applied Information Systems Upper Marlboro, Maryland (USA) 1996 www.slac.stanford.edu/exp/glast/acd/internal/.../ACD-RPT-000042.doc

[111] J. Townsend, C. Smart. Reliability/Risk Analysis Methods and Design Tools for Application in Space Programs NASA Marshall Huntsville, AL.AIAA 98-5276

[112] http://onair.mediafly.com/Podcasts/Episodes/Episode_056_C17_Single_Line_PDF_Presentation_for_Pawel/DownloadMedia/Tim_Covington_C17_Single_Line.pdf

[113] AUTAS, GRD1-2001-40133: AUTomating FMECA for Aircraft Systems; partners: Alenia Aeronautica, Eurocopter, Israel Aircraft Industries, NLR, OCC'M, Sofreten, Technical University of Munich, University of Torino. http://www.di.unito.it/ autas/

[114] C. Picardi, L. Console, F. Berger, J. Breeman, T Kanakis. AUTAS: a tool for supporting FMECA generation in aeronautic systems. mqm.in.tum.de/publications/2004/picardi-et-al-PAIS.pdf

[115] R. C. Bromley, E. Bottomley. “Failure modes, effects and criticality analysis(FMECA),” British Aerospace

[116] Military Aircraft Division.1994 The Institution of Electrcal Engineers Printed and published by the IEE. Savoy Place. London WCZR OBL. UK

[117] B. G. Dale and P. Shaw, “Failure Mode and Effects Analysis in the U.K. Motor Industry: A State-of-Art Study,” Quality and Reliability Engineering International, 1990(6):184.

[118] J. R. Aldridge, J. Taylor, B. G. Dale, The application of failure mode and effects analysis of an automotive components manufacturer, Int. J. Qual. Reliab. Manage. 1990(8):44–56.

[119] B. G. Dale,P Shaw. FMEA in the UK motor industry.Quality and Reliability Engineering International.1990,6(3):179-188.

[120] K. Onodera. “Effective techniques of FMEA at each life-cycle stage. Proceedings of the annual reliability and maintainability symposium,” Piscataway: Institute of Electrical and Electronics Engineers Inc; 1997. pp. 50–6.

[121] K. G. Johnson, M. K. Khanb.A study into the use of the process failure mode and effects analysis (PFMEA) in the automotive industry in the UK.Journal of Materials Processing Technology. 2003(139): 348–356.

[122] B. S. Neagoe.Solutions for the Improvement of the Failure Mode and Effects Analysis in the Automotive Industry. Recent Researches in Manufacturing Engineering.127-132 http://www.wseas.us/e-library/conferences/2011/Brasov2/MEQAPS/MEQAPS-25.pdf

[123] Texas Instruments Inc. Semiconductor Group, “FMEA Process,” June1991

[124] Failure Mode and Effects Analysis (FMEA): A Guide for Continuous Improvement for the Semiconductor Equipment Industry Technology Transfer, September 30, 1992

[125] M. A. Cusumano, “Software Factories: Japan,” Tech Monitoring by SRI International, April 1991, pp. 1-5

[126] K. Matzumura, “Improving Equipment Design Through TPM,” The Second Annual Total Productive Maintenance Conference: TPM Achieving World Class Equipment Management, 1991

[127] Relex, FMEA Software. Reliability Studio 2007 V2. http://www.relex.com/

[128] Reliasoft Cooperation, FMEA Software. Reliasoft Xfmea. <http:// www.reliasoft.com/xfmea/index.htm/>

[129] FMEA Software. Reliability Workbench 10.1. http://www.isographsoftware. com/rwbovernew.htm