SRB Field Joints Failure Analysis Using Fuzzy FMEA

Kouroush Jenab[1], Raymond M. Blecher[1] & Saeid Moslehpour[2]

Abstract

The Challenger space shuttle disaster was due to failure of a solid rocket booster field joint. The NASA management and engineering team's failed in utilizing Failure Mode & Effect Analysis (FMEA) in proper identification and communication of critical system failure modes and their effects. The benefits of fuzzy logic and its application to FMEA methodology could have made a major difference in the outcome as it would have provided more granularities to the risk priority rating. This study reports a platform for performing FMEA that utilizes a conflict resolution module in order to dilute the conflict in risk priority ratings. The platform has been applied to a real case to demonstrated the its application.

1. Introduction

The Challenger disaster was a major loss, not only to the families of the crew, but to the space program as well. This event set the space program back months due to the scale of the failure. To make matters worse, the failure could have been prevented if certain processes had been incorporated and communication between all stakeholders had been open and conducted frequently (NASA, n.d.). If the development team had taken the time and applied a fuzzy Failure Mode and Effect Analysis (FMEA) on the system design and processes - could the disaster have been prevented? The purpose of this paper is to determine if fuzzy FMEA with some innovation could have prevented the Challenger disaster.

[1] College of Aeronautics, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114-3900, USA.
[2] Hartford University, West Hartford, CT 06117, USA.

A little background on the failure and SRB design will provide better insight on the failure and measures that could have been taken to mitigate the risk. The Challenger disaster is centered on the failure of the solid rocket booster (SRB) field joint. You might be asking - what is a SRB field joint?

Each shuttle requires extra propulsion to exceed the weight to thrust ratio required to break the earth's gravity and enter into space. The amount of liquid fuel required would have induced too much weight for the shuttle to overcome and exit the earth's atmosphere safely or re-enter if fuel tanks were still attached due to aerodynamics and the additional weight. To address this issue the shuttle is launched into orbit with two solid rocket boosters that separate after it breaks earth's orbit and enters space. Due to the length and size of the boosters they are constructed in four sections, or segments, so they can be shipped separately and are later mated together. The overall length of one booster is around 150 feet, which would make it very difficult to transport as a single unit (NASA, n.d.). The boosters do not utilize liquid fuel as it would require oxygen to burn. Therefore, each section is filled with a solid fuel that provides its own oxygen as it burns. Now the question that may be asked is how do they assemble the segments together? Since the segments had solid fuel poured into them prior to shipping – welding them together would not be a very wise idea.

The operation and construction of the SRB field joint is fairly simple: each segment has Segment Tang and Segment Clevis that allows the mating of the two segments to each other (shown in Figure 1). The tolerance for each of these is very specific in order to ensure proper mating and sealing of the joints and not allow combustion gases to escape. In order to provide a seal and mate the segments together tightly the utilization of 0-rings and special thermal putty is incorporated, after which they are pinned together. This mating is known as "field joints".

Thus the joints are constructed with two O-rings (Primary and Secondary) and Zinc Chromate putty that would be activated by combustion gas pressure which would force the putty into the areas between the segments (NASA, n.d.). The putty provides a thermal barrier to protect the O-rings from combustion gas pressure. The putty is not only used as "gap" filler, but has a secondary purpose of being used as a piston to set the O-rings into place. This process is referred to as "pressure activation". As pressure increases the gapping between the segments will increase, which would be filled by the O-rings as pressure is increased (NASA, n.d). This will be an important fact to remember as it plays an important part in the events that lead to the Challenger disaster.
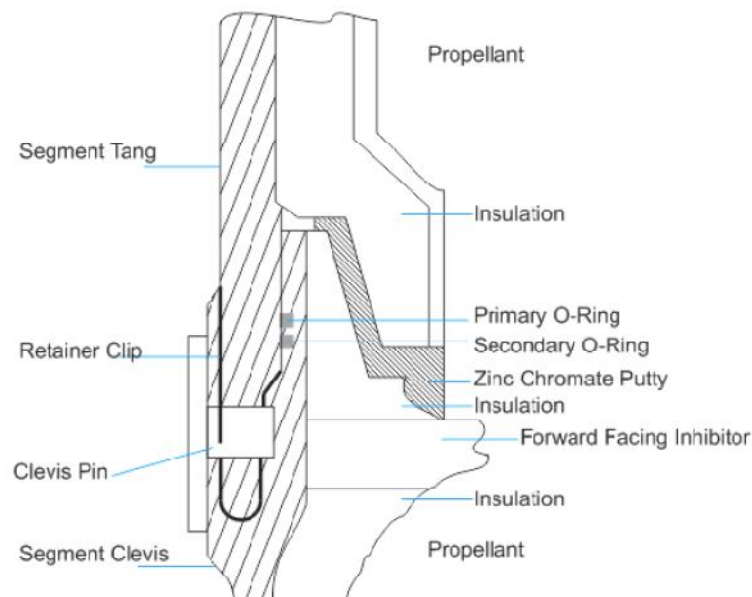
Figure 1- SRB Field Joint (O-Rings Inc, n.d.)

Each segment is pinned to the other, locking the Tang and Clevis joints together. This is accomplished with a Clevis pin, which is secured by both a pin retainer band and a pin retainer clip. The O-rings are placed on the segment Clevis on the inside lip. The problem with O-rings is they are temperature sensitive and their failure could lead to a major event depending on their application, which is another important fact and was the case with the Challenger disaster. The cold weather affected the primary O-ring's ability to respond in time and prevent blow by and erosion of the seal. The secondary O-ring was designed to be a redundant system in such a case, but had also experienced the same response time delay due to the temperature and allowed blow by which led to system failure.

2. Literature Review for fuzzy FMEA

Risk analysis uses several techniques such as FMEA that involves in data gathering, modeling, analysis, and decision. In risk analysis process, the Risk Priority Number (RPN) is used as a factor that scores the system failure effects. The RPN is calculated by Occurrence probability $\times$ Non-detection probability $\times$ Severity of impact. Table 1 presents five scales and their score in the range [1-10] used in traditional FMEA (Jenab et al, 2013).

Table 1: Scores of Failure Factors

Score	Likelihood of Occurrence probability	Likelihood of Non-detection probability	Severity of impact
1	0	0-5	Not detected by customer
2	1/20000	6-15	Slight annoyance
3	1/10000	16-25	Slight annoyance
4	1/2000	26-35	Customer dissatisfaction
5	1/1000	36-45	Customer dissatisfaction
6	1/200	46-55	Customer dissatisfaction
7	1/100	56-65	High degree
8	1/20	66-75	of dissatisfaction
9	1/10	76-85	Safety consequences
10	1/2	86-100	Safety consequences

There has been a lot of research and effort in enhancing FMEA in order to apply it more universally. One such effort has been the application of fuzzy logic in order to overcome weaknesses in Risk Priority Number (RPN). The other is the addition, or more so the reduction, of fuzzy *if-than* rules for certain applications. Herrin (1981) developed a matrix FMEA technique to provide an organized and traceable analysis from the piece-part failure mode through all indenture levels to system level failure effects. In1982, he proposed the Matrix FMEA technique to perform a system interface analysis applicable in a telecommunication system. Lannes (1982) performed cost analysis versus reliability of the design that in a customer point of view is configuration of the system. Takeda (1982) used fuzzy outranking relation in multi-criteria decision for failure mode and effects analysis Kreuze (1983) presented the Built In Test System and its functions along with FMEA derived built in analysis.

Collett and Bachant (1984) addressed a logical extension of FMEA in the Built In Test System, which tested a number of programs and showed a satisfied result and Dussault (1984) provided a survey on FMEA and performed a feasibility study on standardized automated FMEA technique. Jackson (1986) introduced functional circuit analysis as a manual analysis technique that discussed design of the validation task and FMEA. Bednarz (1988) discussed the systems reliability assessment and efficient analysis for FMEA to improve the FMEA. Strandberg and Andersson (1988) proposed a fault simulation approach for FMEA or FTA as a complementary analysis technique. Interdependencies among various causes and effects should be expressed as rules (Keller & Kara-Zaitri, 1989). Bowles and Peláez (1995) developed a model that used linguistic terms for criticality assessment. The model could evaluate the risk associated with item failure modes in a natural way (p. 204).

Yacoub et al. (2000) presented a methodology for risk assessment at the early stage of the development life cycle. Severity analysis was performed by using FMEA as applied to the development life cycle. Since risk was not assessed in detail prior to commencing the project, Kuo and Huang (2000) developed an FMEA model to monitor manufacturing systems and process monitor based on colored Petri Nets. Rosing et al. (2000) extended a fault simulation and modeling of microelectromechanical systems to achieve high reliability and safety. Krasich (2000) developed more symbols for FTA and proposed that FTA be used as a failure mode analysis tool. Goddard (2000) recommended using FMEA for a system during the design phase. He provided SFMEA to assess the safety critical real time control systems embedded in military products. Mena (2000) developed the failure mechanism methodology for integrated circuit assembly and testing.

The two dimensional matrix relating to the failure mechanism was extended. Braglia (2000) developed a new tool for failure mode analysis utilizing economic aspects in FMEA.

The following year, in 2001, a total of nine publications appeared on FMEA. Lee (2001) extended a method that established Bayesian belief network theory to construct a probabilistic directed acyclic graph. This graph is used to represent dependencies between internal and external states in the physical system, such as an electronic component. Zagray (2001) presented an application of FMEA for assessing impact of design changes on reliability in the early design phase. Dong (2001) performed systematic FMEA for designed software employed in a multimedia digital distribution system. The systematic FMEA provided the list of potential failures to establish the corrective action priorities. To reduce the cost of performing FMEA, Considering software development process, Throop et al. (2001) studied the application of verification & validation and hybrid simulation for failure analysis. Performing rotating machines failure analysis, He et al. (2001) discussed the shortcomings of traditional FMEA and proposed the back propagation neural networks. Pillay and Wang (2003) used approximate reasoning in FMEA. They mentioned that precision term should not be forced if data is unreliable. Guimaraes and Lapa (2004) provide reduced if-then rules for FMEA from 125 rules to three sets of 6, 14, and 16 in order to better identify risk. Presentation of a data envelopment analysis approach by Garcia et al. (2005) studied ranking indices among failure modes in fuzzy environemt.

It was determined that results obtained were relative and necessary to perform a new Data Envelopment Analysis (DEA), if design modifications are taken into account or new failure modes are identified (Garcia et al., 2005). There are those who did not agree that the assumption of fuzzy if-then rules be certain or of equal importance and that they could be modified to allow mapping to two different consequences: *High Medium* with 5% confidence and *High* with 95% confidence (Tay & Lim, 2006).

Keskin and Özkan (2008) from Kocaeli University in Turkey conducted a study for a methodology that incorporates fuzzy ART neural network applied to FMEA that allowed the following targets to be reached: evaluation of failure modes with a more mathematical-based method; find solutions to the points at which the classical FMEA methods fail; separation of prioritization of failure modes from sensitivity of participants experience level; and finally the method can be applied simply and easily. Wang et al. (2009) pointed out the strength of fuzzy FMEA and compared fuzzy FMEA with traditional FMEA. Capture FMEA team members' diversity opinions under different types of uncertainties, allowed risk factors and their relative importance weights to be evaluated in a linguistic manner (Hu-Chen et al., 2010). Failure Mode and Effect Analysis is one of the well–known techniques of quality management for continuous improvements of product and process designs, as it relies on determination of risk priority numbers, which indicates the level of risk associated with a potential problem and is a primary factor for its success (Kumru & Kumru, 2012).

A new fuzzy FMEA based on fuzzy set theory and VIKOR method was proposed to deal with risk evaluation problems in FMEA (Liu et al. 2012). It was first proposed by NASA in 1963 as a formal system analysis methodology for their obvious reliability requirements (Dinmohammadi & Shafiee, 2013, p. 2). Kahraman et al. (2013) from the Department of Industrial Engineering at Istanbul Technical University, Istanbul, Turkey, presented a basis for prioritizing problems using FMEA with linguistic variables and fuzzy if-then rules. Severities rating of problems are handled under the categories of catastrophic, major, moderate, and minor events (Kahraman et al.). A paper written by Mandal and Mati (2013) attempts to demonstrate the use of similarity measure value in the FMEA for partially ordering the PRPN values, which are new to this particular domain, and that it is more suitable, than the de-fuzzification process.

Reportedly it takes into account propagation of epidemic uncertainty through the transformation process of input variables (Jenab & Rashidi, 2009; Mandal & Mait, 2013).

3. Fuzzy Failure Mode & Effect Analysis with Conflict Resolution Module

The FMEA method aims to identify problems in processes or products prior to them being evident. First there is a need for an expert knowledge base. Without it there can be no understanding in which to base the logic or *if-then* rules. This knowledge is also applied to the criticality, occurrence, and severity of each identified failure mode along with the known effects (see Figure 2).
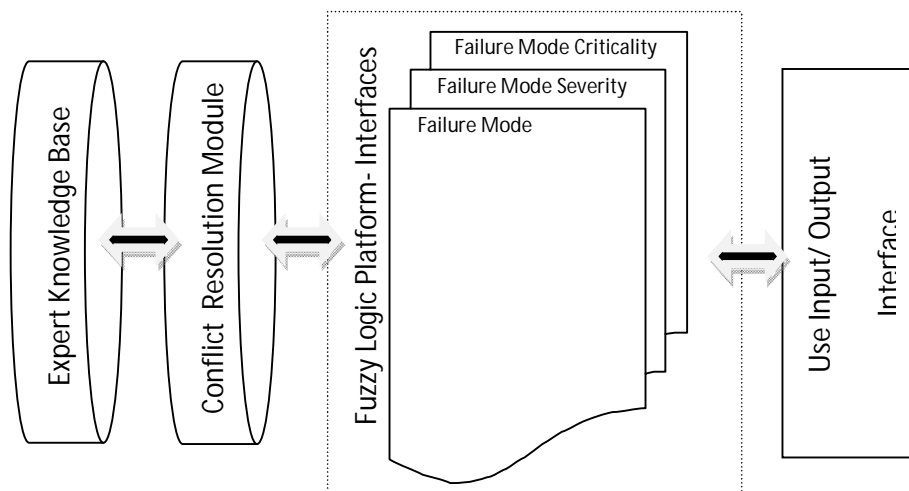
Figure 2 - General Assessment System Architecture

The fuzzy logic toolbox platform consists of three failure mode interface modules and one conflict resolution. Each failure mode fuzzy inference process will be explained with conflict resolution being discussed last. As stated before, the primary problem with traditional FMEA is that there is a high risk of matching PRN and losing sight of which failure mode has the higher priority.

This will be accomplished in a three step process: fuzzification, rule formation, defuzzification. Fuzzification will allow the transformation of traditional crisp inputs (severity, occurrence, and detection) into degrees of membership for each input class. These degrees of membership are calculated by score, percentage, and probability (Jenab & Dhillon, 2004; Jenab et al., 2012). The variables utilized can vary for each model, so the following will be utilized in Table 2 as an example:

Table 2: Fuzzy Variables

Variable	Probability	Percentage	Score
Very High	0.5	0 - 19	9 – 10
High	0.05	20 – 39	7 - 8
Medium	0.005	40 – 59	5 - 6
Low	0.0005	60 – 79	3 - 4
Very Low	0.00005	80 - 99	1 - 2
Extremely Low	0.000005	100	0

The Failure Mode Occurrence Fuzzy Interface Module is based on mean time between failure evaluations. This data is obtained from history records, logs, etc. The relationship of known failure modes on the same level (example: subsystems) are evaluated for interdependencies during the first stage utilizing expert knowledge base rules. The relationship of known failure modes on different levels (example: bottom-up; components, subsystems, entire system) are evaluated for interdependencies during the second stage utilizing expert knowledge base *if-then* rules (Xu et al., 2002). The Failure Mode Effect Severity Fuzzy Interface Module is based on chance of detecting a failure cause. This is evaluated by comparing the severity of a system single failure effect against various combinations of failures (Xu et al., 2002). The Challenger disaster is a good example of what should have happened.

The single failure of the primary O-ring on the SRB field joint should have been evaluated against various combinations of failures with the secondary O-ring and temperature differentials and ring erosion. If this had happened the results may have been adverted.

The Failure Mode Criticality Interface Module is based on possible failure effect outcomes. This is achieved by utilizing two methods: product of likelihood of Occurrence, likelihood of Detection, and Severity of impact that provides the basic formula of S x O x D = RPN and the relationship among the occurrence, detection, and severity using fuzzy knowledge base *if-then* rules so that a risk number can be derived. A fuzzy if-then rule can be presented as '*if x is B then y is C*'. The premise part of the rule 'if' is define by '*x is B*' and the consequent part of the rule 'then' is define by '*y is C*'. The conflict resolution module introduces multiple possibility distribution, which allows for tradeoffs in functions, subsystems attributes or failure factors utilizing compensated operators. The module changes the failure factor and effect, along with their ranking compared to their risk priority category by aggregating expert perceptions of their significance.

Conflict resolution allows for expert knowledge to be applied in a group decision making matrix that identifies failure modes and their risk criteria. Decision makers base their decision upon dependent or independent risk criteria (Jenab & Dhillon, 2004). The user input/output interface in Figure 2 allows for fuzzy inputs which are real time calculations prior to rule evaluation. The fuzzy outputs occur after the rule evaluation and provide critical failure mode, priority for attention, fuzzy RPN, and riskiness. The fuzzy RPN is converted to a crisp PRN for failure mode prioritization, which is called *Defuzzification* (Dinmohammadi & Shafiee, 2013).

The purpose of a fuzzy approach demonstrated above to FMEA is the allowance for partial membership and not absolute one or the other situation when identifying failure modes and their effects. The crisp model makes it difficult to provide precise numerical inputs for the three risk parameters that it requires (Garcia et al., 2005) and relies on whole numbers. There is also the problem that different combinations of the three parameters could provide the same RPN, but in reality would have very different risk potentials (Pillay & Wang, 2003). Finally, H. Gargama, S.K., Chaturvedi, Z. Yang, S. Bonsall, J. Wang, all who have done extensive research in this area pointed out "…that the relative importance among risk parameters are not taken into account while calculating the RPN Value" (Mandal & Maiti, 2013). This is the reason for applying fuzzy logic to FMEA and the value it brings. So was the FMEA properly utilized, and if so, what was missed that if identified would have helped prevent the Challenger disaster? In order to answer the question presented above, a review FMEA usage by NASA must be reviewed. It is found out that even though FMEAs were conducted, the risks were not always prioritized or probability of occurrence considered for ratings of 1 or 1R. The FMEA criticality classification is shown in table 3.

Table 3: NASA FMEA Criticality (Severity) Ratings

Criticality Category	Potential Effect of Failure
1	Loss of life or vehicle
1R	Redundant hardware element, failure of which could cause loss of life or vehicle
2	Loss of mission
2R	Redundant hardware element, failure of which could cause loss of mission
3	All others
Ground Support Equipment only:	
1S	Failure of safety or hazard monitoring system to detect, combat, or operate when required and could allow loss of life or vehicle
2S	Loss of vehicle system

NASA standard operating procedures at the time of disaster were that all Criticality 1 and 1R items would be treated equally, even though their probability of failure may differ. The O-ring failure mode was identified as Criticality 1, not Criticality 1R, so according to their FMEA the secondary O-ring was not identified as providing redundancy - even though NASA management and Thiokol did according to the design intent. Joint rotation created uncertainty in the ability of the secondary O-ring to seal. This did not seem to be a major concern as there were flights in which the primary O-ring failed and the secondary O-ring sealed in accordance with its design intent (Aeronautics and Space Engineering Board, 1988). The O-ring failures from erosion by blow-by due to temperature changes were identified. The FMEA only identified the primary O-ring failure mode and at the time NASA did not consider cascading failures in their FMEA or failures by subsystems or at the component levels. Even though that temperature was identified as a factor in the erosion of the O-rings, the analysis provided was considered inconclusive and was not provided in the retention rationale, also in the eyes of management reduced the likelihood of an event occurring (Aeronautics and Space Engineering Board, 1988). NASA failure to properly utilize, document, and manage the FMEA for failure modes led to events that at the time were considered unlikely.

4. Illustrative Example

First, let's be realistic, that unless the individuals or teams involved in the design and construction applied the findings and recommendations presented in an FMEA to heart, even a fuzzy FMEA (Jenab & Moslehpour, 2015; Jenab et al., 2015a; Jenab et al., 2015b; Jenab & Kelley, 2015; Jenab & Pineau, 2015), would not have prevented the disaster. Looking back at the NASA FMEA Criticality Ratings, what improvement could have been incorporated to better define and support the data available to leadership and engineers?

One improvement would have been to better define the criticality rating variables to allow for better definitions and separation from their neighbors as shown in Table 4.

Table 4: NASA Modified Criticality (Severity) Linguistic Variables

NASA Variable	New Variable	Probability	Percentage	Score
1	Critical Loss	0.5	0 - 5	10
1S	Critical Loss phased[3]	0.1	6 - 15	9
1R	Critical Loss Redundant	0.05	16 - 25	8
2	Mission Loss	0.01	26 - 35	7
2S	Mission Loss Phased[1]	0.005	36 - 45	6
2R	Mission Loss Redundant	0.001	46 - 55	5
3	Mission Impact	0.0005	56 - 65	4
3S	Mission Impact Phased[1]	0.0001	66 - 75	3
3R	Mission Impact Redundant	0.00005	76 - 85	2
4	Partial System Impact	<0.00001	86 - 99	1
4N	Non-critical	0	100	0

The variables Numbers are the severity, 'S' denotes stage or time factor that may affect the overall severity, 'R' denotes redundancy if in place would reduce the probability of failure, and 'N' denotes non-existent criticality. The process would be to identify the correct variable for the failure mode and then calculate the risk priority criticality based on probability x Percentage x Score. This would have reduced the probability of similar priority ratings as previously experienced by the FMEA and the SRB field joint failure modes. If the FMEA utilized by NASA had incorporated fuzzy logic and conflict resolution the inputs by knowledge experts would have been included in the overall knowledge base.

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[3] Phased refers to time sensitive events that have a limited window of impact to the failure mode.

This would have generated if-then rules that would have identified not only primary or even secondary failure modes, but cascading and interdependencies between systems, subsystems, and components. Appling group based decision making conflict resolution would have provided an enhancement in defining a greater granularity or separation between failure modes and their risk priority levels. If applied to the Challenger project, the results of the new model would have provided expert knowledge for development of *if-then* rules by applying fuzzy logic to not only the system; but subsystems and their components, including their interdependencies. Providing more meaningful linguistic variables reduced similar criticality ratings, as was given to both the primary and secondary O-ring failure modes (the secondary was not identified as a redundancy to the primary).

Identify redundant and time sensitive events that could impact the severity of the failure mode, such as the temperature differential and O-ring response time. Group-base failure effect analysis applied in the conflict resolution allowed for additional expert knowledge to be applied in order for a more realistic risk prioritization of failure modes and their effects.

5. Conclusion

The purpose of this paper was to present Fuzzy Failure Mode and Effect Risk Assessment Approach for SRB Field Joints. The facts and data were available to NASA, but were not communicated in an effective manner in order to stress the importance of the findings to decision makers. The lack of separation between failure modes and their risk priority was not seen as a deficiency in conducting the FMEA, but it became apparent when results were presented to decision makers.

There were many processes that could have been improved upon, such as conducting FMEAs not only from the bottom-up, but from the top-down, cascading failure modes, utilization of fuzzy logic, group decision making, linking of deficiencies between systems, and conducting FMEAs at the component and subsystem levels during the design and manufacturing phases at NASA. Communication is the key to success in any endeavor; the tools that we utilize are just a transport mechanism to the receivers of the information – so they must be clear and concise. This paper presented a modified fuzzy failure mode and effect analysis model with conflict resolution that allowed aggregation and expert knowledge to enhance risk prioritization. The limitations of the model are the human factors involved, which provides the expert knowledge base and its rules. For future work, this model could be enhanced further by embedding conflict resolution as a subroutine to each failure mode interface with the intent to reduce the impact of inconsistence experts in the overall group-based failure effect analysis.

References

Aeronautics and Space Engineering Board (January 1988). Post-Challenger Evaluation of Space Shuttle Risk Assessment and Management. National Academy Press. Washington D.C.

Bednarz, S., (1988). Efficient analysis for FMEA. Proceedings of the Annual Reliability and Maintainability Symposium, 416-421.

Bezdek, J., (1993). Fuzzy models - What are they, and why?, IEEE Transactions on Fuzzy Systems, 1(1), 1-6.

Bowles, B., & Peláez, C. (1995). Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. Reliability Engineering and System Safety, 50(6), 203-213.

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

Collett, R.E., & Bachant, P.W., (1984). Integration of BIT effectiveness with FMECA. Proceedings of the Annual Reliability and Maintainability Symposium, 300 -305.

Dinmohammadi, F., & Shafiee, M. (2013). A Fuzzy-FMEA Risk Assessment Approach for Offshore Wind Turbines. International Journal Of Prognostics And Health Management. Retrieved from https://www.phmsociety.org/sites/phmsociety.org/files/phm_submission/2013/ijphm_13_013.pdf.

Dong, N. (2001). Failure modes and effects analysis for software reliability. Proceedings of the Annual Reliability and Maintainability Symposium, 219 -222.

Dussault, H.B. (1984). Automated FMEA status and future. Proceedings of the Annual Reliability and Maintainability Symposium, 1 -5.

Garcia, P., Schirru, R., & Emelo, F. (2005). A fuzzy data envelopment analysis approach for FMEA. Progress in Nuclear Energy, 46(1), 359-373.

Goddard, P.L. (2000). Software FMEA techniques. Proceedings of the Annual Reliability and Maintainability Symposium, 118 -123.

Guimaraes, A. C. F., & Lapa, C. M. F. (2004). Effects analysis fuzzy inference system in nuclear problems using approximate reasoning. Annals of Nuclear Energy, 31(1), 107-115.

He, Y.Y, Chu, F.L., & Zhong, BL. (2001). A study on group decision-making based fault multi-symptom-domain consensus diagnosis. Reliability Engineering and System Safety, 74(1), 43-52.

Herrin, S.A. (1981). Maintainability application using the matrix FMEA technique. IEEE Transactions on Reliability, R30(3), 212-217.

Hu-Chen Liu, Long Liu, Qi-Hao Bian, Qin-Lian Lin, Na Dong, & Peng-Cheng Xu (2010). Failure Mode and Effect Analysis using Fuzzy Evidential Reasoning Approach and Grey Theory. Expert Systems with Applications. 38(3), 4403-4415.

Jackson, T. (1986). Integration of sneak circuit analysis with FMEA. Proceedings of the Annual Reliability and Maintainability Symposium, 408-412.

Jenab, K., & Dhillon, B. (2004). Group-based failure effects analysis. International Journal of Reliability, Quality and Safety Engineering. 12(4), 291-307.

Jenab, K., & Rashidi, K. (2009). Operational reliability assessment of an aircraft environmental control system. Reliability Engineering and System Safety, 94(2), 456-462.

Jenab, K., Sarfaraz, A., SeyedHosseini, S.M., & Dhillon, B.S. (2012). Dynamic MLD analysis with flow graphs. Reliability Engineering & System Safety, 106(1), 80-85.

Jenab, K., Sarfaraz, A., &Ameli M.T. (2013). A conceptual design selection model considering conflict resolution. Journal of Engineering Design, 24(4), 293-304.

Jenab K., & Moslehpour S., (2015). Failure analysis: Case study challenger SRB field joint. International Journal of Engineering and Technology, 8(6), In Press.

Jenab K. , Fine T., Khoury S., & Moslehpour S. (2015a). Cause-Consequence analysis for NASA's space transportation system (STS)- solid rocket booster (SRB). International Journal of Business and Management, 10(8), In Press.

Jenab K., Khoury S., & Rodriguez S. (2015b). Effective FMEA analysis or not?!. Strategic Management Quarterly, 3(2), In Press.

Jenab K., & Kelley T. K., (2015). Bayesian failure modes and effects analysis: Case study for the 1986 Challenger failure. International Journal of Engineering Research and Technology,4(5), 685-690.

Jenab K., & Pineau J. (2015). Failure mode and effect analysis on safety critical components of space travel", Management Science Letters, 2015, 5(7), 669-678.

Kahraman, C., Kaya, İ., & Şenvar, Ö. (2013). Healthcare failure mode and effects analysis under fuzziness. Human and Ecological Risk Assessment: An International Journal, 10.1080/10807039.2012.737753, 538-552.

Keller, A., & Kara-Zaitri, C. (1989). Further applications of fuzzy logic to reliability assessment and safety analysis. Microelectron Reliab, 29(2), 399-404.

Keskin G., & Özkan, C. (2008). An alternative evaluation of FMEA: Fuzzy ART algorithm. Quality and Reliability Engineering International, 25(6), 647–661.

Krasich, M., (2000). Use of fault tree analysis for evaluation of system-reliability improvements in design phase. Proceedings of the Annual Reliability and Maintainability Symposium, 1-7.

Kreuze, F.J. (1983). BIT analysis and design reliability. Proceedings of the Annual Reliability and Maintainability Symposium, 328-332.

Kumru M., & Kumru, P. (2012). Fuzzy FMEA application to improve purchasing process in a public hospital. Applied Soft Computing. 13(2), 721-733.

Kuo, C-H., & Huang, H-P. (2000). Failure modeling and process monitoring for flexible manufacturing systems using colored timed Petri Nets. IEEE Transactions on Reliability, 48(3), 301-312.

Lannes, W.J. (1982). Cost-effectiveness analysis of substation arrangements. IEEE Transactions on Reliability , R30(4), 212-217.

Lee, H. (2001). Using Bayes belief networks in industrial FMEA modeling and analysis. Proceedings of the Annual Reliability and Maintainability Symposium, 7-15.

Liu, H., Liu, L., Mao, N., & Liu, L, (2012). Risk evaluation in failure mode and effects analysis with extended VIKOR method under fuzzy environment. Expert Systems with Applications, 39(17), 12926-12934.

Mandal, S., & Maiti, J. (2013). Risk analysis using FMEA: Fuzzy similarity value and possibility theory based approach. Expert Systems with Applications, 41(7), 3527–3537.

Mena, M.G. (2000). ADI-FMM, a customized FMEA for process management in the IC assembly and test industry. Proceedings of the 3rd Electronics Packaging Technology Conference (EPTC), 176 -180.

National Aeronautics and Space Administration. (n.d.) Report of the Presidential Commission on the Space Shuttle Challenger Accident. NASA. Retrieved from http://history.nasa.gov/ rogersrep/genindex.htm

O-Rings, Inc (2014). Space Shuttle. O-Rings Inc. Retrieved from https://www.oringsusa.com/ html/space_shuttle.html

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

Rosing, R., Richardson, A.M., & Dorey, A.P. (2000). A fault simulation methodology for MEMS. Proceedings of the Design Automation and Test in Europe Conference and Exhibition, 476 -483.

Schmid, C. (2005) Crisp and fuzzy logic. Retrieved from http://www.atp.ruhr-uni-bochum.de/rt1/syscontrol/node112.html.

Strandberg, K., & Andersson, H., (1988). Dependability testing of switching systems in the design phase. Proceedings of the IEEE International Conference on Communications ICC '88 Digital Technology - Spanning the Universe. Conference Record , 2(1), 841 -845.

Takeda, E., (1982). Interactive identification of fuzzy outranking relation in a multicriteria decision problem. Fuzzy Information and Decision Processes- North-Holland-Amsterdam, 301-307.

Tay, K. & Lim, C. (2006) Application of fuzzy inference technique to FMEA. Applied soft computing technologies: The challenge of complexity. Berlin, Heidelberg: Springer.

Throop, D.R., Malin, J.T., & Fleming, L.D. (2001). Automated incremental design FMEA. Proceedings of the IEEE Aerospace Conference, 7(2), 3451 -3458.

Wang, Y., Chin, K., Poon, K., & Yang, J. (2009). Risk Evaluation in Failure Mode and Effects Analysis using Fuzzy Weighted Geometric Mean. Expert Systems with Applications, 36(2), 1195-1207.

Yacoub, S.M., Ammar, H.H., & Robinson, T. (2000). A methodology for architectural-level risk assessment using dynamic metrics. Proceedings of the 11th International Symposium on Software Reliability Engineering (ISSRE), 210 -221.

Zadeh, L. (1965). Fuzzy Sets, Information and Control, 8(3), 338-352.

Zagray, K.W. (2001). Mechanical life prediction library for appliance components. Proceedings of the Annual Reliability and Maintainability Symposium, 406 -413.