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Effective FMEA Analysis or Not?!

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Abstract

Fuzzy failure mode and effects analysis (FMEA) is a means for identifying risk and opportunities and prioritizing them in order of importance in which solutions can then be implemented. This process leads itself to the creation of quantitative analysis that reveals future events so that actions can be taken to prevent failure or to minimize impacts to the system under development. Once the appropriate subject matter expert FMEA team completes their investigation, the Root Cause and Corrective Action process can proceed because the FMEA process has provided measurable data that highlights the areas where corrective action is to focus. When properly applied this process facilitates a closed loop course by which issues are identified and their risk is weighed with the results leading to the elimination of key contributing factors.

Keywords: FMEA, Reliability, Safety, Maintenance, Failure Analysis

1. Introduction

It was a cold morning on January 28, 1986 when NASA was set to launch STS-51-L from Cape Canaveral, Florida. The Space Shuttle 'Challenger' was to achieve the 25th flight of the American shuttle program. This mission was especially distinctive as one of the crew was a civilian. Christa McAuliffe, the 7th crew member, was a junior high school English and American History teacher.

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She was the first American civilian to be chosen for space flight. On the morning of the flight the temperature was in the low 20s, well below the freezing mark.

The shuttle rested on the launch pad, and soaked all night in sub-freezing conditions. Liftoff ensued at 11:37am EDT, and precisely 73 seconds later the ship exploded over the Atlantic Ocean. The tragedy lead to a 32 month pause for the shuttle program while NASA and the Roger's Commission took time to learn what happened. The investigation identified that it was a failed O-Ring at the right end of the mid segment field joint that led to a breach failure that permitted spewing, burning rocket fuel to invade the External Fuel Tank ultimately causing the Solid Rocket Booster (SRB) and the fuel tank to inadvertently separate (Jenab et al, 2015). This paper will explore the use of advanced failure mode and effects analysis (FMEA) techniques that when accurately applied and followed, examine every requirement and measure every outcome utilizing specific regression control. This activity encompasses all aspects of production, i.e. testing, failure analysis, producability studies, inspection areas, etc (Shafiei-Monfared et al., 2009). and every other element associated with the system in order to verify system acceptability.

2. Literature Review

Risk analysis is the primary component of FMEA. This analysis provides a structured approach thus aiding the system developers with understanding and prioritizing outcomes before completing the risk analysis. This allows the system architects to scrutinize available options in order to address and mitigate risk. This approach typically starts during the system proposal process and becomes an integral part of the program lifecycle. The FMEA process examines latent failure problem solving and requires a holistic view of the solution from concept creation to the end of product life.

System Engineers are required to take under consideration managing all aspects of the system from design, production, support, and ultimately through system delivery. The customary FMEA application centers on three traditional types of risk assessment, the probability of occurrence (O), severity (S) and detection/control (D), and may or may not include opportunities. A risk is a possible future event that threatens the accomplishment of one or more future goals or objectives. Likewise, an opportunity is a potential benefit that could positively affect the program's ability to meet its technical, cost, schedule, financial, or other objectives. Managing risk can be difficult, because of uncertainty; technical circumstances are not always black and white. To aid with the prioritization of risk it is very helpful to measure features by employing fuzzy logic or the assignment of values to typical risk assessment levels, such as Low or Very High.

Developing a scheme that assigns a number based on the level of discourse for each of these items is a way of filtering and sorting these various attributes to obtain a clear indication of which risks require corrective action. In this instance, the indicator is a Risk Criticality Number (RCN) that is obtained using a program specific structure (Jenab & Dhillon, 2005). This value is acquired after evaluating the probability of occurrence, rate of severity/impact, and rate of detection for each risk. It is important to describe the O, S, and D terminology as Abdelgawad & Fayek (2010) explained it:

- Probability of Occurrence (O) is referred to as probability of occurrence and is defined over the range of 1–10.
- Severity (S), which is also referred to as Impact (I), has three dimensions: cost impact (CI), time impact (TI), and scope/quality impact (SI). They are all defined over the range of 1–10.
- Detection (D) is also referred to as detection/control, and is defined over the range of 1–10.
- RCN is defined over the range of 1–1,000.

The misconception with the standard FMEA approach is that it does not accurately represent true life interdependencies of the situation and considers the value of each variation to be equal. Wang, Chin, Poon and Yang (2009) underlined that these independent risk values do not contemplate independent weight variances for each variable, indicating the difficulty with assigning numerals to reveal frequency of failure. To further the debate by addition of simple explanations to highlight failure modes, such as High and Very Low do not clearly indicate which risks require mitigation. As a result, risks connected with the highest assigned are believed to be the highest risk and receive corrective action priority and means. Many methods can be applied to overcome the shortcomings of traditional FMEA Dempster-Shafer Theory (Liu et al., 2005), Grey Theory (Chang et al., 1999), Monte Carlo simulation (Bevilacqua, 2000; Pillay & Wang 2003), Bayesian Nets (Lee, 2001), Master Logic Diagram (Jenab et al., 2012), Flow graph (Jenab & Rashidi, 2009, Jenab et al., 2013). The Fuzzy method is one of many approaches created to address the underlying limitations .

3. Enhancing FMEA with Fuzzy Logic

Before issuing a complete system design, the system engineering team must fully understand the systems functionality characteristics through gathered intelligence gained by executing FMEA iteratively throughout the design phase that leads the project team to comprehend entirely the expected concepts and behaviors of the system under development. A key component of this understanding is acquired by involving all *stakeholders, users, decision makers, subject matter experts, and customers* in the FMEA process. This collaborative effort leads to the System Engineer's (SE's) first attempt at recognizing and categorizing the shortcomings of the system under design by using FMEA to identify single point failures, however additional methodologies are necessary to assess criticality of this analysis in such a way that all design entering can readily determine which failure modes require immediate attention.

One approach to categorizing and prioritizing FMEA results is to employ Fuzzy Logic which allows variables to have a truth value within a defined range instead of a true/false, zero/one value. The Fuzzy Logic process consists of three primary elements that lead to the creation of a risk criticality value. The first element is the linguistic definition of the probability of occurrence, referenced in Table 1 (Abdelgawad & Fayek, 2010). This demonstrates a likely example of how risk will be experienced in this design.

Table 1(Linguistic Definition of the Probability of Occurrence)

Description term	Probability of occurrence
Very high (VH)	>67% (2/3) chance. Event will certainly occur.
High (H)	Between 33–67% (2/3) chance. Event is expected to occur.
Medium (M)	Between 10–33% (1/3) chance. Event may occur.
Low (L)	Between 1–10% chance. Event is unlikely to occur.
Very low (VL)	Less than 1% chance. Event is highly unlikely to occur.

The second component of this process requires the definition of impact or the result should this risk become a reality. The outcome is either going to be cost, schedule, or quality impact. Table 2 (Abdelgawad & Fayek, 2010) illustrates an example of the definition of impact structure.

Table 2 (Linguistic Definition of Impact)

Terms	Impact categories		
	Cost	Time	Scope/quality
Very high (VH)	≥10% of project cost.	In service date delayed ≥ 10% of project duration.	Project scope or quality does not meet business expectations.
High (H)	Cost increase is ≥7% and < 10% of project cost.	In service date delayed ≥ 7% and < 10% of project duration.	Scope changes or quality are unacceptable to project sponsor.
Medium (M)	Cost increase is ≥4% and <7% of project cost.	In service date delayed ≥ 4% and <7% of project duration.	Major areas of scope or quality are affected.
Low (L)	Cost increase is ≥1% and <4% of project cost.	In service date delayed ≥1% and <4% of project duration.	Few areas of scope or quality are affected.
Very low (VL)	<1% of project cost.	Insignificant schedule slippage.	Scope change is not noticeable/quality degradation is not noticeable.

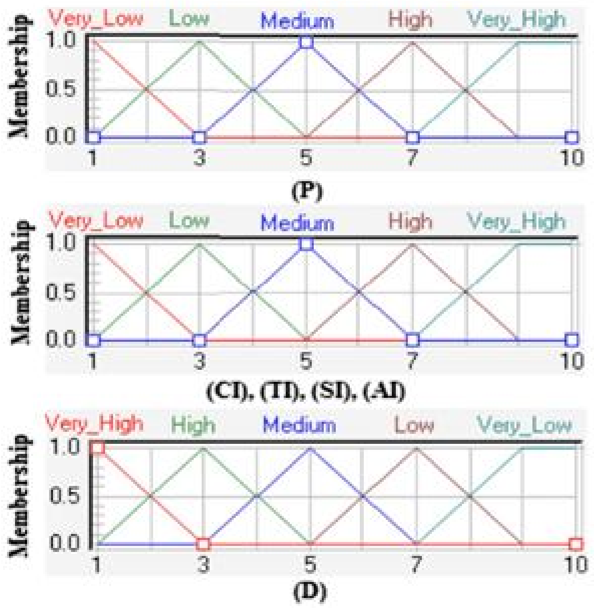
The last element is the detection and control definition. This requires the team to assess the probability that a risk will be detected or that a risk event that has occurred can be controlled. Table 3 (Abdelgawad & Fayek, 2010) is a sample of a detection and control chart.

Table 3 (Linguistic Definition of Detection/Control)

Term	Detection/control
Very low (VL)	The project team was unable to identify a risk response strategy capable of detecting the risk event, controlling root causes, and controlling the consequence of the risk event.
Low (L)	The project team has identified a risk response strategy with a low chance of detecting the risk event, controlling the root causes, and controlling the consequence of the risk event.
Moderate (M)	The project team has identified a risk response strategy with a moderate chance of detecting the risk event, controlling the root causes, and controlling the consequence of the risk event.
High (H)	The project team has identified a risk response strategy with a high chance of detecting the risk event, controlling the root causes, and controlling the consequence of the risk event.
Very high (VH)	The project team has identified a risk response strategy that has been proven in the past to have high effectiveness in detecting the risk event, controlling the root causes, and controlling the consequence of the risk event.

These concurrent functions require input from the appropriate subject matter experts to create a solid foundation in which the designers can assess potential hazards. Once the foundation is settled, the design team must then establish separate membership functions illustrating the range for probability of occurrence, impact, and detection/control. In the example present in Table 4 (Abdelgawad & Fayek 2010), trapezoidal membership functions are used.

Table 4 (example)



The X axis of these scales represents the value of discourse; the Y axis describes the degree of membership. The probability and impacts membership functions for probability of occurrence, CI, TI SI, and AI have an inverse relation with detection/control membership. The integrated process team leader must now develop the membership function definition that shows the relationship between the input variables and to the output risk critical numbers (RCN). The RCN is value between 1 and1000. If-then-rules are then established to cover all combinations of the input variables and RCN values are establish in which corrective action is required. This process creates the structure for prioritizing system risks uniformly and thus allowing all program designers, not just the SMEs, to determine when a risk requires mitigation. If this method had been used during the design of the space shuttles solid rocket motor boosters, the outcome may have been different for the Challenger mission.

4. Effectiveness of FMEA Discussion via an Example

The space shuttle employs two solid rocket motors containing 550 tons of propellant, and each extended steel tube is 149.1 ft. in length, and 12.2 ft. in diameter. The SRB's were designed to provide the majority of shuttle's lift-off thrust.

The primary component of each unit includes the motor, separation system, operational flight instrumentation, recovery system, pyrotechnics, deceleration system, and range safety destruct system. Each SRB encompasses four solid rocket motor segments. For ease of manufacture and transport, the SRB's were built and delivered to the Kennedy Space Center in four separate tubular segments that traveled by rail car to Cape Canaveral. Once the segments reached the Space Center, the elements were linked and secured at attachment points called 'field joints'. These joints fastened each segment together using seventy-seven steel pins that were sealed with an uncomplicated rubber O-ring that was insulted from internal heat and combustion with fire retardant Zinc Chromate putty.

In 1985 Roger Boisjoly an aerodynamicist at Mortaon Thiokol, wrote a memo to his superiors warning them of the consequences of a marginal SRB system design. The original O-ring used in the design did not easily return to its original configuration in cold temperatures. Ring pitting and erosion caused by hot combustion gasses was also a mistake of the design. Furthermore, resiliency testing confirmed low temperature was a problem. At low temperatures the rings failed to expand and seal the joints effectively. The resulting warping allowed actuating gas pressure to find gaps and escape the seal. Further testing concluded the gaskets would not characteristically seal when the SRB's flexed during flight. During the 32 month halt of the program, field joint improvements had to be made. To start with, a new tang capture feature was added to offer metal to metal interface that surrounded the tang and clevis ends of the coupling sections. The reliability of this design predicts the seal will not leak under twice the expected pressure loads.

Custom shims are also installed between the outer surface of the tang and out clevis leg that controls the O-ring to assist with proper O-ring compression. An additional leak port has been incorporated and the O-ring is placed so that it also serves as a thermal barrier in case insulation is breached. The heat block putty has also been replaced with a pressure actuated flap. Segment attach pins have been replaced with a retainer band to ensure enhanced shear strength. External heaters also now ensure consistent O-ring temperature. Solid research of the challenger failure clearly captures that test analysis was regularly performed and accurately identified single point failures in the 'O' rings. However research never revealed where potential failures were ranked and prioritized. Had fuzzy logic been applied, Roger Boisjoly would have had more decisive data that would have demanded program management take evasive action. This position is furthered because the fuzzy logic process would have required input from a diverse pool of subject matter experts well before FMEA actions would have occurred.

Therefore, any risk that would have tripped the program established threshold would result in corrective action.

5. Conclusion

The firm application of Fuzzy FMEA could have greatly improved the chances of mission success for the Space Shuttle Challenger. FMEA diagnostics performed with surgical precision would have identified recurring problems and identified the need for containment of the issues and defects at hand. Immediate actions could have been taken when FMEA analysis identified the 'O' Ring as a single point failure due to the lack of redundancy systems and would have identified other contributing key design factors. Furthermore, had management quickly accepted the possibility of this issue being a high priority (mission failure) risk and addressed the immediate problem the results of the FMEA could have further led to the creation of improved regression test points.

Through Improved test data, engineering would learn if the process is repeatable, to either validate that the risk has been fully recognized and corrected or expose the need for further investigation until the non-compliance is fully addressed. It is the authors' belief that the ineffective use of testing or the use of QA techniques/FMEA did not facilitate this senseless disaster. Since 1982 NASA knew O-rings were a dangerous failure point known to require a redundant backup plan. Furthermore, high pressure testing performed by Morton Thiokol further exposed marginal design limits and concluded redundant seals were inadequate. Rather, it could be poor and irresponsible program management at NASA and Morton Thiokol underestimated the reality and complexity of the situation. This underestimation was due to leadership's ineffective communication and unrealistic demand setting, because their focus was solely on cost and schedule constraints that outweighed mortal value.

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