Proceedings of DETC2002
ASME2002 Design Engineering Technical Conferences
Montreal, CANADA, September 29-October 2, 2002

DETC2002/DFM-34185

Life Cost-Based FMEA Incorporating Data Uncertainty

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ABSTRACT

Failure Modes and Effects Analysis (FMEA) is a design tool that mitigates risks during the design phase before they occur. Although many industries use the current FMEA technique, it has many limitations and problems. Risk is measured in terms of Risk Priority Number (RPN) that is a product of occurrence, severity, and detection difficulty. Measuring severity and detection difficulty is very subjective and with no universal scale. RPN is also a product of ordinal variables, which is not meaningful as a proper measure. This paper addresses these shortcomings and introduces a new methodology, Life Cost-Based FMEA, which measures risk in terms of cost. The ambiguity of detection difficulty and severity is resolved by measuring these in terms of time loss. Life Cost-Based FMEA is useful for comparing and selecting design alternatives that can reduce the overall life cycle cost of a particular system. Next, a Monte Carlo simulation is applied to the Cost-Based FMEA to account for the uncertainties in: detection time, fixing time, occurrence, delay time, down time, and model complex scenarios. This paper compares and contrasts these three different FMEAs: RPN, Life Cost-based point estimation, and Life Cost-Based using Monte Carlo simulation for data uncertainty.

Keywords: FMEA, Life Cost-Based FMEA, Monte Carlo Simulation, Failure Cost

1. INTRODUCTION

1.2. Introduction to FMEA

Failure Modes and Effects Analysis (FMEA) is a tool widely used in the automotive, aerospace, and electronics industries to identify, prioritize, and eliminate known potential failures, problems, and errors from systems under design before the product is released (Stamatis, 1995). Several industrial FMEA standards such as the Society of Automotive Engineers, US Military of Defense, and Automotive Industry Action Group employ the Risk Priority Number (RPN) to measure risk and severity of failures. The Risk Priority Number (RPN) is a product of 3 indices: Occurrence (O), Severity (S), and Detection (D). Design engineers typically analyze the “root cause” and “end-effects” of potential failures in the sub-system or component. The analysis is organized around failure modes, which link the cause and effect of failures. Traditional FMEA sheets limit failure representation to only a couple of columns to describe the entire fault chain (Lee, 2000), inhibiting the understanding of the true cause of failures. Thus, a more thorough analysis, such as scenario based FMEA (Kmenta, 2000), can be used to understand all intermediate effects between the initiating cause to end effects.

1.2. Shortcomings of Traditional FMEA

One definition of detection (D) difficulty is how well the organization controls the development process. Another definition relates to the detectability of failure on the product is in the hands of the customer. The former asks “What is the chance of catching the problem before we give it to the customer?” The latter asks “What is the chance of the customer catching the problem before the problem results in a catastrophic failure?” (Palady, 1995) These definitions confuse the FMEA users when one tries to determine detection difficulty. Are we trying to measure how easy it is to detect where a failure has occurred or when it has occurred? Or are we trying to measure how easy or difficult it is to prevent failures?

The 3 indices used for RPN are ordinal scale variables that are used to rank-order industries such as, hotels, restaurants, and movies. Ordinal values preserve rank but the distance between the values cannot be measured since a distance function does not exist. Thus, the product or sum of ordinal variables is not meaningful. The RPN is a product of 3 independent ordinal variables.

For example suppose you want to plan a weekend getaway with your spouse and evaluate the satisfaction level using 3 different indices: hotel, restaurant, and play. Let us use a scale from 1 to 5 for each category and come up with 2 alternatives: trip "A" and trip "B". For Trip "A" you'll stay at a 5 star hotel, dine at a 4 star restaurant, and watch a 5 star play. Using the RPN technique, the product of the 3 indices for trip "A" yields 100 points. For trip "B" you're on a tighter budget so you decide to stay at a 4 star hotel, dine at a 3 star restaurant, and watch a 3 star play. The product of the 3 indices for trip "B" yields 36 points. The difference in satisfaction level between trip "A" and trip "B" is almost 3 fold. But can you really guarantee that your spouse will be 3 times more satisfied had you taken her/him on trip "A"? The answer is "no". We can probably make a safe conclusion that your spouse will be more satisfied with trip "A" since all 3 categories scored higher compared to trip "B" but we cannot conclude that trip "A" is 3 times better than trip "B". As seen from this example, measuring risk in terms of RPN does not really make a whole lot of sense.

1.3. Related Research

Recent FMEA research has been focused on improving traditional FMEA limitations by using different measurement schemes, considering multiple failure scenarios, and incorporating sensitivity analysis. Selected samples of recent research in FMEA include the following:

- Tracing causal chains and their probabilities using Bayesian Networks (Lee, 2001).
- Using a Petri net to analyze multiple failure effects (He, 2001)
- Identifying and prioritize the process part of potential problems that have the most financial impact on an operation (Tarum, 2001)
- Using probability of a certain failure and the probability that this failure will not be detected to obtain expected failure cost (Gilchrist, 1993)
- Using RPN on a logarithmic scale (Ben-Daya, 1996)
- Applying Monte Carlo simulation on RPN numbers (Bevilacqua, 2000)

These new FMEA approaches have addressed some of the problems mentioned in the previous section but not yet adequately addressed how to: 1) determine failure cost, 2) address sensitivity analysis, and 3) resolved confusion with detection.

The investigation presented in this paper builds upon earlier research (Kmenta, 2000), which is based on scenario-based FMEA to weigh the expected life cost of failure during the early part of design. This paper will introduce a life cost-based FMEA that addresses the shortcomings in the previous methodology and introduces sensitivity analysis using Monte Carlo simulation. Next we will present a case study example on a flange and apply the traditional FMEA, life cost-based FMEA, and sensitivity analysis on the life cost-based FMEA. Finally, we will compare the 3 results and review the limitations and conclude with future research.

The case study for this paper was done in conjunction with and supported by research and development being performed at the Stanford Linear Accelerator Center (SLAC) for the Next Linear Collider (NLC). All of the quantitative estimates in this work should be considered as illustrative only, and do not reflect what the actual costs might be at some time in the future.

2. TYPES OF FMEA METHODOLOGIES

2.1. Traditional RPN

A traditional FMEA uses RPN to assess risk in three categories: Occurrence (O), Severity (S), and Detection (D). The rating is scaled from 1 to 10 for each category.

The occurrence is related to the probability of the failure mode and cause. Occurrence ratings have been standardized by many electronics and automotive industries (AIAG, 1995) over the last few years. A 10 on the occurrence table corresponds to a failure happening with every other part. A 1 corresponds to one failure in a million parts.

The severity index measures the seriousness of the effects of a failure mode. Thus, a severity index is assigned to the end effect of a failure. A 1 on the severity index corresponds to a failure that does not affect anything, a 5 corresponds to a performance loss, a 7 corresponds to machine shut down, and a 10 corresponds to a life-threatening failure.

The detection index is generated on the basis of the likelihood of detection by relevant design reviews, testing, and quality control measures. A 1 on the detection index corresponds to a failure mode that is almost certain to be detected and a 10 corresponds to a failure that is almost impossible to detect. Taking the product of these three indices (occurrence, severity, and detection) generates the RPN. The RPN represents the risk associated to each failure mode.

2.2. Life Cost-Based

To resolve the ambiguity of measuring detection difficulty and the irrational logic of multiplying 3 ordinal indices, a new methodology was created to overcome shortcomings, Life Cost-Based FMEA. Life Cost-Based FMEA measures failure/risk in terms of cost. Cost is a universal language that can be easily understood in terms of severity among engineers and others. Thus, failure cost can be estimated using the following simplest form:

$$\text{Expected Failure Cost} = \sum_{i=1}^{n} p_i c_i \qquad (1)$$

p: Probability of a particular failure occurring
c: Cost associated with that particular failure

Table 1. Life Cost-Based FMEA Table

			Time (hours)								Cost		
Scenario	**Effect of Failure**	**Occurrence**	**Origin**	Det Phase	Detection Time	Fixing Time	Delay Time	Recovery	Quantity	Labor Cost	Material Cost	Total Cost
Compression Ratio too low	Leak	4	Install	Install	8	4		0	1	7,200	480	7,680
Over compressing	May not seal later	4	Install	Install	8	4		0	1	7,200	1,920	9,120
Flexible (Wrong material)	Leak	0.1	Des	Install	8	2	8	0	400	12,240	19,200	31,440
Pinching during assembly	Leak	10	Install	Install	8	4		0	1	18,000	4,800	22,800
Scratches on the O-Ring	Leak	20	Install	Install	8	4		0	1	36,000	9,600	45,600
Wrong Material (permeability)	Leak	0.1	Mfg	Install	8	2	8	0	400	12,240	19,200	31,440
Size is too big or too small (design)	Leak	0.05	Des	Design	1	24		0	1	188	24	212
Water drips onto joint - operation	Leak	1	Oper	Oper	8	2	8	40	1	402,700	480	403,180

Table 1 shows a Life Cost-Based FMEA table created for the methodology. An occurrence value that is larger than 1 indicates the expected number of failures during manufacturing, installation, or during operation. An occurrence value of less than 1 indicate the probability of such a failure happening during the design stage, which is a one-time event for many cases. Thus, the life-cycle cost reflects only a fraction of the failure cost that is proportionate to the probability of occurrence.

Failure origin indicates when the failure has been initially introduced. Detection phase indicates the stage at which the failure has been realized. Figure 1 shows the four different initiating stages (design, manufacture, installation, operation) and the failure detection stages (design review, inspection, testing, operation), and an example where failure is detected during operations stage and the initial origin of the failure is a design error. Due to design error, the part has to be redesigned, remanufactured, and reinstalled. There may be some delay between each activity also. Recovery time is the time the system is inoperable due to failure. Recovery time is associated with lost opportunity.

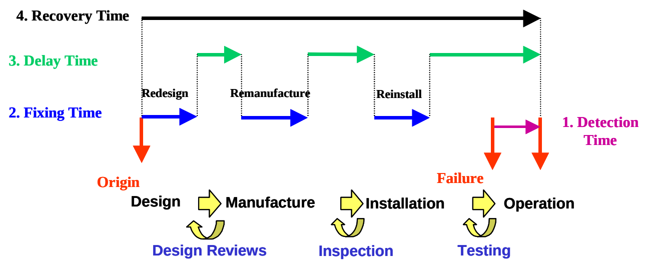


Figure 1. Initial Origin and Detection Stages of Failure

Failures may occur at any stage of the life cycle and can be detected either during the same stage or during subsequent stages. The failure cost is minimal when the origin and detection occur during the same stage. The failure cost increases as the origin and detection stages become further apart.

Failure cost has three major components: labor cost, material cost, and opportunity cost. Labor cost and opportunity cost can be measured in terms of time and can be further broken up into four different stages: detection time, fixing time, delay time, and recovery time.

- **Detection Time**: Time to realize and identify a certain type of failure has occurred and diagnoses the exact location.
- **Fixing Time**: Time to fix the problem. The actual fixing time for each individual component.
- **Delay Time**: Time incurred for non-value activity such as waiting for response, set up time, and mailing/shipping time.
- **Recovery Time**: Time to have the system up and running to its original state. Only applies to failures that happen during the operations stage.

Examples of failures during the design stage are incorrect design calculations, incorrect number in prints, and incorrect material selection. These mistakes may be detected during design reviews before the components are manufactured or in the subsequent stages. Failure cost is minimized when failure and detection occurs in the same stage. The most expensive failure is which originates during the design stage and does not get detected until operation (customer detection).

Examples of failures during the manufacturing stage are operator's mistake, bad material calibration, and incorrect type of material being used. These mistakes can be detected during parts inspection or in the subsequent stages. Examples of failures during the installation stage are following incorrect installation procedure, applying too much or too little force on to tools when tightening fasteners, damaging the part, etc. Labor cost can be derived with the time information obtained in the cost-based FMEA table using the following equation:

$$\text{Labor Cost} = \text{Occurrence} \times \{[\text{Detection Time} \times \text{Labor rate} \times \text{\# of Operators}] + [\text{Fixing Time} \times \text{Labor rate} \times \text{\# of Operators} \times \text{Quantity}] + [\text{Delay Time} \times \text{Labor rate} \times \text{\# of Operators}]\} \quad (2)$$

Component replacement due to failure is considered as material cost. Material cost is obtained using the following equation:

$$\text{Material Cost} = \text{Occurrence} \times \text{Quantity} \times \text{Cost of Part} \quad (3)$$

Opportunity cost is the cost that incurs when a failure inhibits the main function of the system and prevents any creation of value. Opportunity cost is discussed in detail in section 3.2.2.

2.3. Life Cost-Based with Monte Carlo Simulation

Life Cost-Based FMEA uses point estimation for its analysis. The danger with using point estimation is the potential for misinterpretation of the average numbers. Plans based on average conditions are incorrect since one does not know if the condition has reached the upper or lower thresholds. A sensitivity analysis on the estimates will provide better confidence in the result and make for a better understanding of which variables are the cost drivers.

A Monte Carlo simulation is applied to the Life Cost-Based FMEA to perform a sensitivity analysis on the variables associated to failure cost: occurrence, detection time, fixing time, and delay time. A triangular distribution using minimum, mode, and maximum value was used. There are many distribution systems one can use for the simulation; however, with limited past history data and using estimated variables, a triangular distribution was selected.

3. ACTUAL APPLICATIONS

3.1. Case Study

The Stanford Linear Accelerator Center (SLAC) is a national research laboratory that is charged with finding the most basic elements of matter. Engineers at SLAC are currently designing the Next Linear Collider (NLC) that is 20 miles long, 10 times longer than the current linear collider at SLAC. A component of the NLC, called the RF (Radio Frequency) Delay Line Distribution System (DLDS) Waveguide System, will consist of 180 kilometers of tubing (20,000 pieces of tubing) to carry microwave power from the power sources to the accelerated structure. The flange that connects the DLDS pipes are used as a case study for this paper. The NLC requires a total of 20,000 identical flanges to connect the DLDS pipes.


(a) (b) (c)

Figure 2. Flange Types: (a) Quick Release, (b) Welded, (c) Conflat

Three different types of flanges; quick release type, welded type (Aluminum, Al, & Stainless Steel, SS) and the conventional conflat flange (SS) as shown in Figure 2 are considered for the case study. The scope of the FMEA analysis is limited to the flange's mating surface and the attachment of flange to the pipe.

The participants identified three major functions of the flange: hold vacuum, radio frequency (RF) compatibility, and disconnection for service. The analysis was performed for two different periods of time. The first period, a pre-operation period, includes design, manufacture and assembly and was assumed to comprise the first two years of operation. The second period is the operational period, extending over the 20-year expected life cycle of the NLC. The analysis was done this way because it is believed that most of the failures and most of the design changes will occur during the pre-operation period. An assumption was made that the majority of the failures identified in the pre-operation period would be resolved by the operation period. However, there are some failure modes that only occur after a significant time into operation such as radiation damage on the O-ring and corrosion.

Breakdown of the flange and pipe cost is shown in Table 2. The pipes are assumed to be 35 ft long. The expected cost of a 35 ft aluminum pipe is $170. However, due to stringent tolerance requirements for the DLDS, the actual pipe cost is estimated to be $280. For copper pipe the material cost is $1.47/lbs, which corresponds to $540 for a 35ft long copper pipe. With post processing, the expected copper pipe cost is $640.

Table 2. Cost of Pipe and Flanges

	Quick Release	Welded	Welded	Welded	Conflat	Conflat
Flange material	Al	Al	SS	SS	SS	SS
Pipe material	Al	Al	Cu	Al	Al	Cu
1 Pair of Flanges	$120	$15	$50	$1000	$1000	$240
End Forming/ welding	$ 80	$80	$80	$30	$30	$80
Pipe	$280	$280	$640	$280	$280	$640
Total	$480	$375	$770	$1310	$1310	$960

Three different designs are considered for cost comparison for the welded flange. One type has the flanges end-formed as in the case of the quick release type (Al to Al). The welded type uses a peeling mechanism to detach the joints. Thus, the joint will only have a finite number of times it can be peeled off before having to replace the whole flange itself. The additional cost of end-forming the pipes is assumed to be the same as for the quick release type. The other two designs are stainless steel flange on either aluminum or copper pipe. Since connecting stainless steel on to aluminum or copper is not trivial, a transition material is required for the flanges. The flange made of transition material is expected to cost $1000. The labor cost for welding stainless steel is estimated $50. Copper pipe costs $530, as copper is almost 3 times denser compared to aluminum. A center ring is also required to align the two pipes.

Failure is defined as an unwanted behavior in a system. Depending on the life cycle of a system, failure cost can exceed the acquisition cost of a system. This paper will compare 3 different types of FMEA analysis: RPN, determining failure cost as a point estimate, and applying sensitivity analysis to failure cost analysis. The cheapest alternative for each design was selected for the case study analyses: quick release (Al-Al), welded (Al-Al), conflat (SS-Cu).

During the operations period, two types of activities exist: regular maintenance and fixing due to unexpected failures. For this case study, regular maintenance on the flanges during the 20-year life cycle is not considered since maintenance is not required on the flanges. Thus, only unexpected failures will be taken into account during the operation stage.

3.2. Comparison of FMEAs

3.2.1 Traditional RPN

Failure scenarios were investigated for the 4 different flanges (Quick release Al-Al, Welded SS-Al, Welded SS-Cu, Conflat SS-Cu). A combined total of 74 different failure scenarios were identified related to the flanges: 55 failure scenarios during the pre-operation and 19 different failure scenarios for operation period. Next, RPN numbers for each failure scenario were assigned following the traditional FMEA rule. The rating is scaled from 1 to 10 for RPN.

The occurrence ratings table for the two different periods was created to accommodate credible levels of failure. For the pre-operations stage, a 1 on the occurrence rating scale corresponds to one failure during the first two-year period on any given 20,000 pairs of flanges in the NLC's DLDS. Since the expected life cycle of the system is 10 times that of pre-operation stage, or 20 years, the occurrence rating for the operation period was scaled by 10 to that of the pre-operation stage. A 10 on the occurrence table corresponds to a failure happening every week.

The severity index measures the seriousness of the effects of a failure mode. Thus, a severity index is assigned to the end effect of a failure. A 1 on the severity index corresponds to a failure that does not affect anything, a 5 corresponds to a performance loss, a 7 corresponds to machine shut down, and a 10 corresponds to a life-threatening failure. The flanges used for the DLDS do not pose any life-threatening failures. Thus, a 10 for severity was not assigned to any failure modes for this analysis.

Detection index is generated on the basis of likelihood of detection by relevant design reviews, testing, and quality control measures. A 1 on the detection index corresponds to a failure mode that is almost certain to be detected and a 10 corresponds to a failure that is almost impossible to detect.

The risk priority number (RPN) is generated by taking the product of these three indices: occurrence, severity, and detection. The RPN represents the risk associated to each failure mode. Figure 3 shows a Pareto chart of the RPNs for the 4 different flange designs obtained for the pre-operation period.

The highest risk of failure for the quick release flange during the pre-operation period occurs when the scientists give wrong specifications for the design, e.g., tolerance and vacuum requirement. The next highest potential risk is scratches on the mating surfaces due to poor parts handling and poor quality control. These failure modes may lead to leakage. A joint becoming loose is the next highest potential failure. Failures due to O-ring compression ratio being too low or radiation damage on the O-ring is a problem that occurs during the operation period. These failures are critical for the quick release type during the operation period. Geometric alterations due to external forces imply tools being dropped on the parts causing geometric alterations. Porosity implies defects in the material structure that occurs during the material processing stage. A wrong number in print implies a mistyped number or numbers that are misread from the prints.

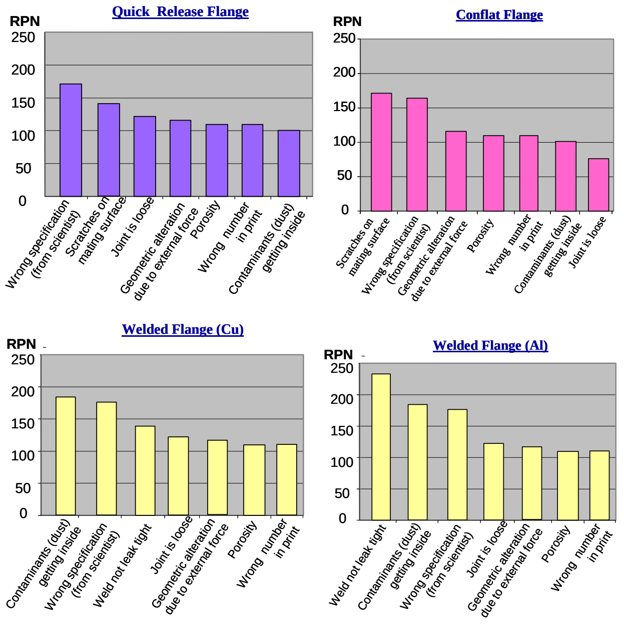


Figure 3. RPN During Pre-Operation

The welded flange poses a risk of not providing a leak tight joining method. Aluminum had a RPN of 240 compared to the Cu, 144, because it is more difficult to weld. This RPN was found to be the highest of all the failure modes among the four different types of flanges examined. The risk of contaminants getting inside the tube is much greater for the welded design since oxidation is more likely to occur during the welding operation. The total RPN for the quick release type is 35% higher than the other two types during operation. The RPN for the welded flange scored higher for the pre-operation period (RPN = 2530) compared to the operation period (RPN = 1104) because most of the failures occur during the welding operation. Failures during operation will not be discussed since the majority of the failure modes are found during pre-operation stage.

The conflat flange has a higher risk of leakage from scratches due to the hard copper gaskets being in contact with the mating surface. Scratches lead to leaks, and conflat flanges are more prone to this kind of risk compared to the other two.

Table 3 shows the overall RPN, including the operation period, obtained for the 3 different designs (the two welded designs are combined since the difference in RPN was minimal). The highest RPN, 4078, is associated with the quick release type. This is due to the fact that more failure scenarios were identified that was contributed to the O-ring failures for the quick release types. Eleven more failure scenarios were identified with the quick release flanges compared to the welded design. During the operation period, welded and conflat types seem to be more reliable when compared to the quick release type (RPN of 1104 & 1115 vs. 1486). The overall RPN shows that the conflat type has the lowest risk compared to the other types.

Table 3. Risk Priority Number from FMEA

	Quick Release	Welded	Conflat
Pre-Operation	2592	2530	2032
Operation	1486	1104	1115
Total	4078	3634	3147

3.2.2. Life Cost-Based FMEA

The Life Cost-Based FMEA sheet, as shown in Table 1, was conducted for each of the 3 flange designs separately. First, the origin of the failure and the detection stages were identified for each scenario. An occurrence value was assigned to each scenario based on how many times such an event would occur during the pre-operation and operation period. Any design errors, such as giving wrong tolerance or calculating the dimensions incorrectly, has an expected failure rate of 5%. This is derived from past experiences at SLAC. Since the flange is a simple design, we assumed that a design error to be a onetime mistake.

An assumption is made that manufacturing mistakes are detected during parts inspection or in the subsequent stages. An assumption was made that a batch order is 100 pairs of flanges. Thus, any re-work due to manufacturing error will account for 100 pairs of flanges. Some may argue that this cost can be neglected since the final assembler or the end customer is not liable. However, someone has to pay for the manufacturing failure cost.

Examples of failures during the installation stage are misalignment, joint not tight, gap in joint, and scratches on the mating surface. The pipes will be installed by one sector at a time (each sector has 400 pipes). Thus, to ensure proper installation, vacuum and alignment check is conducted after each sector is built.

Examples of failures during the operation stage are water dripping on to joint, thermal expansion of the tubes, and support system poorly engineered. Any type of failure that occurs during this stage has a high penalty since the NLC will be shut down. SLAC estimates the lost opportunity due to shutdown to be \$10,000/hour. After the failure has been resolved, the system has to be evacuated to 10^{-7} Torr. This could take up to 2 times the period for which the system has been shutdown. A coefficient of 3 is used in the multiplication factor to account for the shutdown and setting the conditions of the NLC to its running state. Recovery time is obtained using the following equation:

$$\text{Recovery Time} = \{\text{Detection Time} + \text{Fixing Time} + \text{Delay Time}\} \times 3 \qquad (4)$$

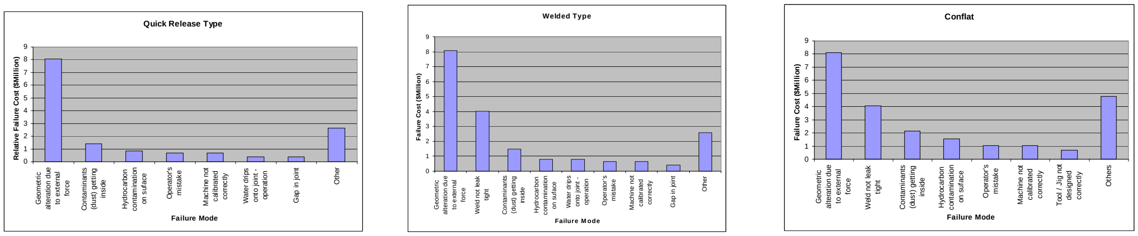
Knowing recovery time, we can estimate the opportunity cost for the NLC using the following equation:

$$\text{Opportunity Cost} = \text{Recovery Time} \times \$10{,}000 \qquad (5)$$

Fixing time can be broken down into 3 different stages: joint disassembly, pipe replacement, and vacuum. Joint and pipe replacement time is multiplied to the total number of flanges affected, while vacuum time is only applied one time to the whole sector. Time to pump down a full sector is assumed to be 6 hours.

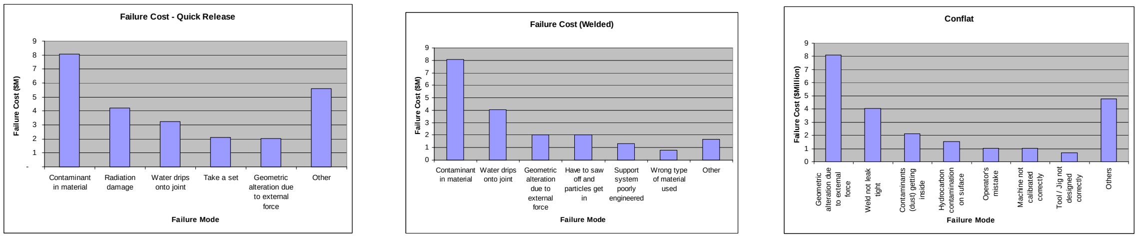
Quantity describes whether a failure affects an individual flange, a batch, a sector, or the entire system. A localized failure would require a simple replacement of a single pipe. A failure detected at the manufacturing stage would result in scrapping the entire batch and re-manufacturing (100 flanges). A failure detected during the installation stage would require flanges in that sector to be replaced (400 flanges). A failure that occurs far beyond the first two years in operation may require all of the 20,000 flanges to be replaced. Labor cost is obtained using Equation 2 with \$50/hr for labor rate and assumes 3 operators are required to detect and fix the problems. As discussed in section 2, part cost includes the cost of the flange, end forming the pipes, attaching the conflat onto the pipe, transition material for the conflat, and the pipe. Flanges for the quick release and welded type will be end-formed onto the pipes. Thus, when a failure occurs, the entire pipe has to be replaced. In that respect parts cost will embody the cost of the flange and the pipe.

The estimated failure costs for the 3 different flanges during pre-operations stage are shown in Figure 4. The most significant difference in failure cost between the three different designs is that the conflat flange has a \$4M additional failure cost compared to the quick release and welded flanges because conflat flanges have to be welded to the pipes.



(a) Quick Release (b) Welded **(c) Conflat**

Figure 4. Expected Failure Cost During Pre-Operation



(a) Quick Release **(b) Welded** **(c) Conflat**

Figure 5. Expected Failure Cost During Operation

Figure 5 shows failure cost during operations stage for the 3 different designs. The quick release type has additional failure costs compared to the weld and conflat such as radiation damage on the O-ring and the O-ring taking a set. These O-ring failures are accountable for the $6M additional failure cost.

The total failure cost for the 3 different flanges is shown in Table 4. The result shows that there is no significant difference between the 3 flange types in terms of failure cost. 35 – 50% of the total failure cost is expected to incur during the pre-operation stage. Quick release was the most economical design during the pre-operation period and conflat turned out to be the most expensive. As a single event failure cost during pre-operations, gas trapped with low conductance was the most expensive type of failure ($4.8M). The second most expensive failure is a bad design that causes a leak in the pipes ($1.6-$1.7M). This type of failure would be caught during testing after installing a sector. However, these failures are due to design errors and the probability of these types of failures actually occurring is estimated to be 5%. Thus, in estimating the failure cost for design errors, only one twentieth of the failure cost due to design is considered ($0.8M).

Although conflat flanges have less number of identified failures, replacing a conflat is more expensive in terms of material and labor cost since the conflat requires a transition material to have it attached to the pipe. The $4M difference between the welded/conflat type and the quick release type is mainly due to the weld not being leak tight. It is most likely that the failure would be identified during the operations period. Furthermore, downtime and number of frequencies for this type of failure makes the welded type undesirable. The most costly type of failure is geometric alteration due to external forces on the flanges. External forces result from poor handling of the pipe and flange during installation or fixing. A slight geometric alteration that may be unnoticed can cause RF failure in the system. The participants estimate such an occurrence to happen 20 times during the life cycle of the NLC.

The most expensive type of single event failure during the operations period is the thermal expansion of the tubes causing RF failure or a leak in the system. This failure requires all 20,000 pipes be replaced. Thus, the failure cost ranges from $12 - $19M depending on the type of flange used. This failure is very expensive because it is a design error that is caught at the operation stage, and all 20,000 flanges and pipes would need to be replaced.

Table 4. Failure Cost from Cost-Based FMEA (Point Estimation)

	Quick Release	Welded	Conflat
Pre-Operation	$15.2 M	$19.3 M	$23.3 M
Operation	$25.1 M	$19.8 M	$19.9 M

3.2.3. Monte Carlo Simulation

A Monte Carlo simulation is applied to the Life Cost-Based FMEA to consider the sensitivity of the variables associated to failure cost: occurrence, detection time, fixing time, and delay time. A triangular distribution using minimum, mode, and maximum values was used. As an example, Table 5 shows the range of fixing time used for the simulation for the 3 different flanges.

Table 5. Range of Fixing Time (min) for Flanges

	Quick Release			Conflat			Welded		
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Joint Replacement	20	30	100	40	60	90	50	60	120
Pipe Replacement	30	90	180	30	90	180	30	90	180
Vacuum	240	360	480	240	360	480	240	360	480

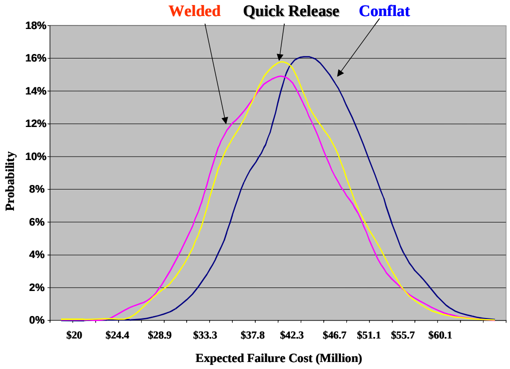


Figure 6. Life Cycle Cost with 100% Shutdown Simulation

From past history, only 30% of the failures that occur during operations require the system to be shut down. 70% of the time, the failures can be ignored until the next periodic maintenance period. Thus, a discrete distribution on recovery time was incorporated into the simulation. The purpose of this simulation is to simulate for the 70% of the failures that happen during operation stage that do not require an immediate shutdown of the system. This factor has a significance impact on the overall failure cost since 1 hour of downtime is equivalent to a $10,000 loss. Recovery time can vary from 40 to 80 hours depending on the severity of the failure. The result of the simulation with a distribution curve is shown in Figure 6 and 7 for the 3 different designs. The mean failure cost has reduced dramatically after incorporating the 30% shutdown, as shown in Table 6.

Table 6. Life Cycle Cost with Simulation

	Quick Release	Welded	Conflat
100% Shutdown	$40.5M	$39.9M	$43.3M
30% Shutdown	$22M	$16.9M	$20.6M

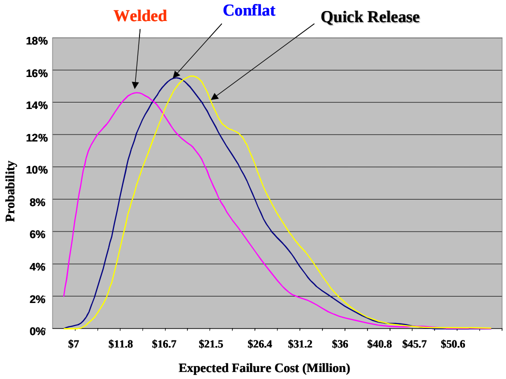


Figure 7. Life Cycle Cost with 30% Shutdown Simulation

4. DISCUSSION OF THE COMPARISON STUDY

Since FMEA is not a design selection tool, we cannot conclude based upon the overall RPN that the conflat flange is the best solution and that the quick release type is a bad choice. The RPN version identifies potential failure modes for different designs and the degree of risk associated with each design. Design selection depends not only on risk, but also on the life cycle cost; FMEA using RPN does not address this issue. The RPN version shows how potential risks differ between the three designs and encourages the engineers to think ahead about how to further reduce risks prior to finalizing the design. However, there is a fundamental problem of multiplying three independent ordinal variables.

With the Life Cost-Based FMEA, the failure cost for the 3 designs do not differ significantly. All 3 designs have an expected failure cost of $40M. The surprising fact is that even after applying the Monte Carlo simulation, the mean expected failure cost for the 3 different designs did not change. However, with the 30% shutdown criteria, a difference in mean failure cost can be noticed. The welded type did turn out to be cheaper than the rest. A summary of the 3 different FMEA is shown in Table 7.

Table 7. FMEA Comparison Chart

	RPN	Life Cycle Failure Cost						
		Point Est.	Monte Carlo w/ 100% Shutdown			Monte Carlo w/ 30% Shutdown		
			5%	50%	95%	5%	50%	95%
Quick Release	4078	$40.3	$31.3	$40.5	$50.0	$13.1	$22.0	$33.7
Welded	3634	$39.1	$30.8	$39.9	$49.8	$7.9	$16.9	$28.9
Conflat	3147	$43.2	$34.4	$43.4	$52.3	$11.6	$20.6	$32.7

Units: Million Dollar

What is interesting from the 3 different analysis is that not only do the methods give different results, but the most critical failures also differ among the 3 different methods. Here are the top 3 failures modes from each method:

- Traditional FMEA using RPN:
    1. Water drips onto joint
    2. Contaminant in material
    3. Bad material selection

- Life Cost-Based FMEA (Point Estimation):
    1. Geometric alteration due to external force
    2. Weld not leak tight
    3. Contaminant in material

- Life Cost –Based FMEA with Monte Carlo:
    1. O-ring radiation
    2. O-ring taking a set
    3. Geometric alteration due to external force

Comparing the RPN and Life Cost-Based FMEA we see that the top 3 failure modes are completely different. The main reason for the O-ring failure having such a high cost is that if it fails, all of the O-rings have to be replaced and this is most likely to happen during the operation period. When we analyzed the O-ring failures using the traditional RPN, this fact was overlooked and was not captured in the analysis. Thus, the Life Cost-Based FMEA forces the user to think of all the consequences.

Table 8. Failure Cost from Top 3 Failure Modes

Method	Failure Cost
RPN	$ 1.1 M
Life Cost-Based	$ 5.2 M
Life Cost-Based with Monte Carlo	$ 11.5 M

Table 8 summarizes the consequences of the top 3 failure modes from the 3 different FMEA methods in the event a 30% shutdown for applicable failures. As seen from this table, the consequence of selecting the appropriate FMEA methodology can change the failure cost savings by an order of magnitude.

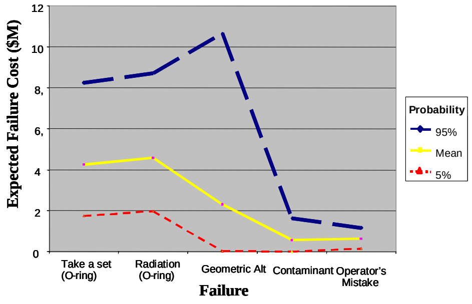


Figure 8. Top 5 Failure Modes for Quick Release

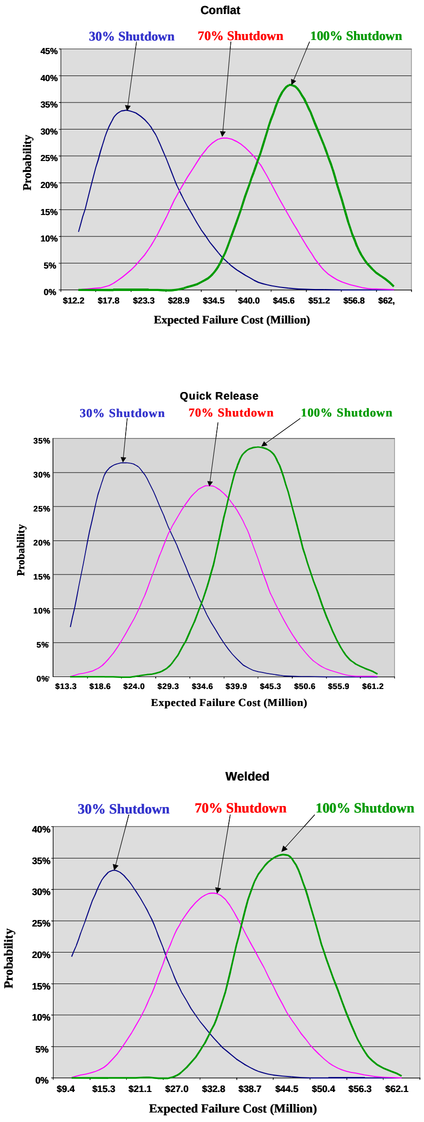


Figure 9. Life Cycle Cost with Different Shutdown Probabilities

An in-depth analysis on the top 5 failure modes using Life Cost-Based FMEA with Monte Carlo simulation is shown in Figure 8. As seen from the figure, the mean failure cost is ranked in the following order: O-ring radiation, O-ring taking a set, geometric alteration, contaminant, and operator's mistake. However, the 95th percentile line indicates that there is a 5% chance that geometric alteration can cause more than $11M in damages. Thus, this failure mode should not be overlooked. Geometric alteration, contaminant, and operator's mistake have a 5% chance of not incurring any cost since there is a 70% probability that the system will not have to be shut down due to these failures. However, O-ring failures require immediate attention and maintenance cannot be postponed until the next maintenance period.

The 30% shutdown variable is most sensitive in terms of cost compared to other variables: occurrence, detection time, fixing time, or delay time. Thus, failure cost was plotted for 30%, 70%, and 100% shutdown probabilities for different flanges in Figure 9.

The ranking of life cycle cost has changed with the 30% shutdown simulation. The change in magnitude of life cycle cost is the smallest for the quick release type for different shutdown probabilities. This is because, two types of O-ring failures, taking a set and radiation damage, require the system to shutdown. It is assumed that when radiation damage on the O-ring is detected, all of the O-rings will be replaced with a mandatory shutdown of the system. Thus, the 30% shutdown probability is overruled for these cases. These two failures are accountable for $5M in life cycle cost.

5. CONCLUSIONS

This paper compared three different FMEAs: traditional RPN, Life Cost-Based, and Life Cost-Based with Monte Carlo simulation, using flange as a case study. The three methods showed very different results and demonstrated the implications of using different FMEA methods by calculating the top 3 failure life-cycle costs from each method. The case study has shown that failure cost can differ up to an order of magnitude between RPN and the Life Cost-Based with Monte Carlo simulation. Life Cost-Based FMEA allows design comparison which was not possible using traditional RPN FMEA. Thus, this methodology can be used early during the conceptual design stage to determine design alternatives. Trade-offs between design and life cycle cost can be achieved using this methodology.

The most significant impact of Life Cost-Based FMEA is that it 1) completely eliminates the ambiguity of detection and using the product of ordinal numbers to measure risk, 2) measures risk in terms of cost, 3) facilitates trade-offs between designs and reducing life-cycle cost.

As shown in Table 8, life cycle cost savings is an order of magnitude different depending on which failures to resolve in the design phase. Selecting the 3 highest cost driven failures from the Life Cost-Based FMEA clearly show its advantage over the RPN or point estimated cost based FMEA. Life Cost-based FMEA with Monte Carlo simulation enables designers pick the best design in terms of cost benefits.

The life cycle cost of the whole system can be easily obtained with additional information such as development, manufacturing, installation, and additional operation costs. Using the life cycle cost analysis, engineers can truly compare design in terms of financial aspects. The research in this paper lays out a concrete foundation to measure design failures in terms of cost by eliminating the detection ambiguity and using an interval-scale as a measurement.

ACKNOWLEDGMENTS

The authors would like to thank Stanford Linear Accelerator Center for providing the opportunity for this research, and especially Karen Fant, Carl Rago, Jeff Rifkin, and Stephen Marnock for their valuable time for this research, and other NLC staff members who provided us with valuable technical information and to Larry Chao and Ravi Jain for making comments on this paper.

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