ECONOMIC IMPACT

FAILURE MODE AND EFFECTS ANALYSIS

By

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ECONOMIC IMPACT

FAILURE MODE AND EFFECTS ANALYSIS

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Abstract: Failure mode and effects analysis (FMEA) is a method for reducing or eliminating failure modes in a system. A failure mode occurs when a system does not meet its specification. While FMEA is widely used in different industries, its multiple limitations can cause the method to be ineffective. One major limitation is the ambiguity of the risk priority number (RPN), which is used for risk prioritization and is the product of three ordinal variables: severity of effect, probability of occurrence, and likelihood of detection. There have been multiple attempts to address the RPN’s ambiguity, but more work is still needed. Any new risk prioritization method needs to have a decision-support system to determine when to implement a corrective action or improvement.

This research addresses some of the shortcomings of traditional FMEA through the creation of a new method called Economic Impact FMEA (EI-FMEA). EI-FMEA replaces the three ordinal values used in the RPN calculation with a new set of variables focusing on the expected cost of a failure occurring. A detailed decision-support system allows for the evaluation of corrective actions based on implementation cost, recurring cost, and adjusted failure cost. The RPN risk prioritization metric is replaced by the economic impact value (EIV) risk prioritization metric which ranks risks based on the impact of the corrective action through the largest reduction in potential failure cost. To help with resource allocation, the EIV only ranks risks where the corrective actions are economically sustainable.

A comparison of three FMEA methods is performed on a product, and the risk prioritization metrics for each method are used to determine corrective action implementation. An evaluation of the FMEA methods are shown, based on the expected failure cost reduction, using the decision-support criteria of each method.

The EI-FMEA method contributes to the body of knowledge by addressing the ambiguity of the RPN in FMEA by creating the EIV risk prioritization metric. This allows the EI-FMEA method to reduce failure cost by providing a decision-support system to determine when to implement a corrective action when both finite and infinite resources are available.

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TERMINOLOGY

AFC	Adjusted failure cost
CA	Corrective action
CFC	Corrected failure cost
CMC	Ceramic matrix composite
CNC	Computer numerical control
COPRAS-G	Grey-complex proportional assessment method
CoQ	Cost of quality
C_{PK}	Process capability
CTE	Coefficient of thermal expansion
DFMEA	Design FMEA
EFC	Expected failure cost
EI-FMEA	Economic Impact FMEA
EIV	Economic impact value
FMEA	Failure mode and effects analysis
FMECA	Failure modes, effects and criticality analysis
FRPN	Fuzzy risk priority number
HDD	Hard disk drive
IF-TOPSIS	Intuitionistic fuzzy-Logic technique for order by similarity to ideal solution
LC	Labor cost
LCB-FMEA	Life Cost Based FMEA
LPC	Lily Pad Computers
MC	Material Cost
MCM	Monte Carlo simulation method
MIL-STD	Military Standard
MLE	Maximum likelihood estimator
MTBF	Mean time between failure
MTTF	Mean time to failure
MTTR	Mean time to repair
NASA	National Aeronautics and Space Administration
NSWC	Naval Surface Warfare Center
OC	Opportunity cost
PFMEA	Process FMEA
RPN	Risk priority number
RPN_c	Cost-oriented RPN

SB-FMEA	Scenario Based FMEA
SME	Subject matter experts
SOD	Severity of effects, probability of occurrence, and likelihood of detection variables
TB	Terabyte
TEC	Total expected cost
WDC	Western Digital Corporation

CHAPTER I

INTRODUCTION

This chapter introduces the research topic, motivation for choosing the topic, the research significance, and the research problem and purpose statements. This chapter concludes with the research questions that will guide the research methodology.

1.1 Research Thrust

The major thrust of this research is the improvement of quality through the reduction of failure cost in a manufacturing environment. *Quality* is a product's ability to meet its specification and be free of deficiencies (Juran & Godfrey, 1999), which create non-value-added cost in a product. These non-value costs are the costs associated with finding, repairing, or reworking failures. To be competitive in the marketplace, a company needs to improve quality by minimizing failure cost (Saleem, Nisar, Khan, Khan, & Sheikh, 2017). This research will investigate ways to reduce failure cost using failure mode and effects analysis (FMEA).

1.2 Motivation and Significance

Today's companies face global competition in three primary areas: faster product development, reduction of costs, and high customer expectations for a quality product (Carlson, 2012). A company with long production development times, high costs, and low quality will not survive in the competitive environment. FMEA is a failure-prevention method that, when used correctly, addresses all three areas, but certain limitations to the traditional FMEA can make the method ineffective (Jiang, Xie, Wei, & Zhou, 2016). Further development of the FMEA method is needed to address the limitations and create an effective process.

1.3 Problem Identification

Manufacturing companies are looking for ways to manufacture high-quality products to be competitive in a global marketplace (Saleem et al., 2017). A high-quality product is a product that meets its specifications, provides customer satisfaction, and is free from deficiencies in the manufacturing process (Juran & Godfrey, 1999). New product designs and existing products benefit from failure-prevention methods that enhance quality, particularly through cost-effective prevention methods (Bohan & Horney, 1991; Cheah, Shahbudin, & Taib, 2011; Feiring, Sasfri, & Mak, 1998). FMEA is a common prevention method, but it has inherent limitations. A review of 75 different studies lists multiple instances of ambiguity in the risk priority number (RPN) risk prioritization metric and the input variables (i.e., severity of effects (S), probability of occurrence (O), and likelihood of detection (D), referred to as the SOD variables in this research) that make up the RPN as a major limitation to the FMEA method (H.-C. Liu, Liu, & Liu, 2013).

Table 1-1. Common Themes in RPN Value Ambiguity

Ambiguity of RPN value	Number of Studies
Relative importance among SOD variables is not taken into consideration	45
Different combinations of SOD variables produce the same RPN value, but risk may be different	33
SOD variables are subjective and difficult to determine	21
RPN multiplication is an incorrect mathematical operation	14
RPN value cannot be used to measure the effectiveness of corrective actions	12
Large gaps in RPN values make it difficult to determine the impact of corrective actions due to holes in the RPN achievable scale	10

Note. Adapted from H.-C. Liu et al. (2013).

1.3.1 Problem Statement

Failure mode and effects analysis is a method for reducing or eliminating failure modes in a system. A failure mode occurs when a system does not meet its specification. FMEA uses the RPN to prioritize the allocation of available resources to failure modes (Guo, Li, & Wolf, 2016). The ambiguity of the RPN risk prioritization metric in FMEA, however, produces inconsistent risk prioritization (L.-Y. Chen & Yeh, 2014; Gargama & Chaturvedi, 2011; Kmenta & Ishii, 2005). The cost associated to improve the system quality (i.e., system meeting the specification) can be between 20%–50% of sales, thus reducing a company’s ability to be competitive in the marketplace (Dahlgaard & Dahlgaard, 2002; Gupta & Campbell, 1995; Sandoval-Chávez & Beruvides, 1998). Any new risk prioritization method needs to have a decision-support system to determine when to implement a corrective action (CA) or improvement (H.-C. Liu, You, Li, & Su, 2016).

1.4 Research Purpose

Since 1992, there has been an exponential growth in FMEA studies that use an alternative method to the RPN value for risk prioritization (H.-C. Liu et al., 2013). The growth in studies is also significant over the past 10 years with 40 studies between 2007 and 2011 and hundreds of studies between 2012 and 2016 (Figure 1-1).

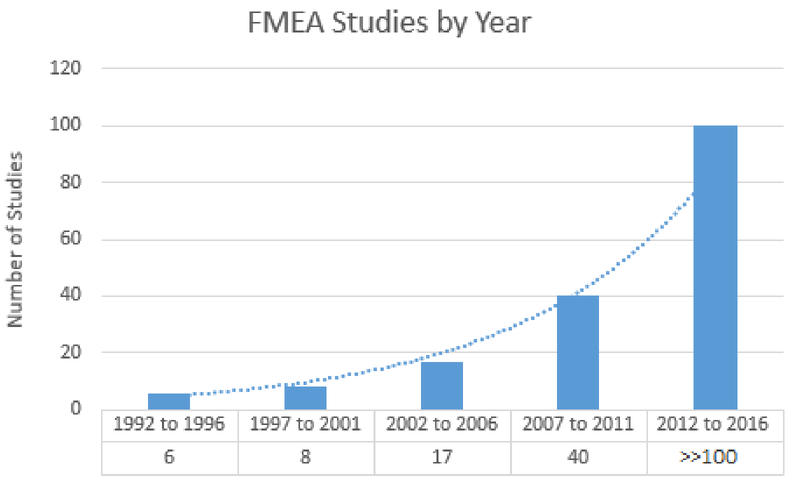


Figure 1-1. FMEA studies by timeframe.

Note. Adapted from H.-C. Liu et al. (2013).

The three most popular methods for addressing the ambiguity of the RPN metric are fuzzy-based studies, grey theory, and cost-based analysis (H.-C. Liu et al., 2013). Fuzzy-based studies and grey theory use weighting factors and membership functions with linguistic SOD variables that do not address the underlying weakness of the RPN metric. Cost-based studies replace the SOD variables with two ratio scales for probability of failure and cost of failure to address the ambiguity of the RPN prioritization metric (Kmenta & Ishii, 2005; Rhee, 2005), but the studies do not define economic factors for corrective action or resource allocation and are limited in their risk ranking.

1.4.1 Purpose Statement

The purpose of this research is to develop an economic-impact-based failure mode and effects analysis that uses an economic-risk-prioritization metric to prioritize risk and determine resource allocation in a manufacturing environment.

1.4.2 Research Questions

During the research, I evaluate two main research questions.

1. *How can risk be prioritized to reduce failure cost?*

2. *How are finite resources allocated to reduce failure cost?*

1.5 Summary

Companies face competition on a global scale and need to have products with high quality and low non-valued added costs. FMEA is a dependability analysis method used to help identify potential failure modes in a product, but inherent limitations to the method can cause the process to be ineffective. The following research investigates ways to address certain limitations to the traditional FMEA process to make it more effective.

CHAPTER II

BACKGROUND OF THE STUDY

This chapter analyzes the body of knowledge pertaining to failure mode and effects analysis, starting with an introduction to the cost of quality (CoQ) and explaining how FMEA fits within the concept. An introduction to FMEA follows, which includes a brief history, the use of FMEA, and how to perform an FMEA. Next, the limitations of FMEA are discussed, followed by an evaluation of prior studies and their attempt to address the limitations. This chapter concludes with the current state of the problem and support for further research.

2.1 Cost of Quality

The *cost of poor quality* is a term coined by Joseph Juran in the early 1950s in his *Quality Control Handbook*. Juran defines the cost of poor quality as the costs associated with finding and fixing products that do not meet their intended purpose or specification (Juran & Godfrey, 1999). The CoQ includes costs associated with preventing failures and is the total cost to produce a product which meets the specification (Bohan & Horney, 1991). It is a collection of four cost categories: prevention, appraisal, internal failure, and external failure. Gupta and Campbell (1995) describe the four categories as follows: prevention costs are the costs associated with building quality into a product; appraisal costs are the costs associated with making certain a product meets the specification or requirements; internal failure costs are the costs associated with a product not meeting its specification, as found by the manufacturer; and external failure costs are the costs associated with a product not meeting its specification, as found by the customer.

Equation 2-1: Cost of quality

$$CoQ = P + A + IF + EF$$

$where\ P = Prevention\ costs, A = Appraisal\ costs, IF = Internal\ failure\ costs, and\ EF = External\ failure\ costs.$

2.1.1 Types of Costs

There are two groups of costs in the CoQ: voluntary and involuntary. Voluntary costs are the proactive costs paid to reduce or prevent failure, and involuntary costs are the reactive costs paid to fix failure. Prevention costs and appraisal costs are voluntary while internal and external failure costs are involuntary (Sandoval-Chávez & Beruvides, 1998). Prevention costs are funds invested to reduce the amount of failures, or *non-conformances*, in a product, often through quality planning, process planning and control, dependability analysis, and training (Juran & Godfrey, 1999). Dependability analyses are specific tools for identifying and reducing failures. These tools include fault tree analysis, reliability block analysis, petri net analysis, Markov analysis, and FMEA.

Appraisal costs can determine if a product conforms to its specification by using incoming inspection and test, in situ inspection and test, final inspection and test, document review, and product quality audits (Juran & Godfrey, 1999).

Internal failure costs occur when an item is found to be non-conforming to its specification(s) before it leaves the manufacturing plant. These costs, which can increase quickly, may include scrap, rework, repair, failure analysis, and lost or missing information (Juran & Godfrey, 1999). The costs associated with failure can include the dollar amount of the product being scrapped or reworked, the time to determine the root cause of the failure, the costs to implement a change, extra in situ testing or inspection, the lost time cost associated with downtime, or potential costs for missing delivery dates. Lost or missing information costs are the costs associated with collecting information which should have been supplied with the product. For example, an operator uses the weight of a wind-turbine blade to match a set of blades for a given wind-turbine system, but the weight data are not collected in the factory operating system. The operator then must spend time tracking down the weight data from a previous weight operation and is not currently adding value to the wind-turbine system. None of these internal failure costs would exist if a product conforms to its specification at the time of production and has no deficiencies (Juran & Godfrey, 1999).

External failure cost occurs when an item is found to be non-conforming to its specification after it leaves the manufacturing plant and the customer has received it. These costs can include warranty charges, returns, product recalls, complaint investigations, allowances or discounts made to a customer, poor-quality penalty fees, lost opportunities in sales, lawsuits, and lost perceptions of quality (Juran & Godfrey, 1999). External failures are the most expensive cost category in CoQ calculations. Once a product leaves the manufacturing facility, the cost associated with a non-conformance or deficiency is significantly higher than if the issue is found at the manufacturer (Gupta & Campbell, 1995). Portions of external costs are easy to quantify (e.g., warranty charges, complaint investigations, allowances, and poor-quality fees); however, lost opportunities in sales and lost perception of quality are not easy to quantify. It is hard for a company to know the exact cost of a non-conforming product reaching the market place.

2.1.2 External Failure Cost Effects

In September 2015, investigators found Volkswagen modified their engine-control software to give a false positive reading on their diesel engine vehicles during emissions testing. The modification allows the vehicle to pass the emissions test and revert to the standard software during normal use, which puts out emissions higher than allowable. The software modification is found on approximately 11 million vehicles built over a period of 8 years (Atiyeh, 2017). The backlash against Volkswagen has been swift and fierce. Two weeks after the violation became public, the stock price decreased by over 40%. Volkswagen currently has multiple pending class action lawsuits, some from different governments. In the fall of 2016, Volkswagen came to a settlement with the United States Department of Justice for approximately $15 billion dollars (Bomey, 2016). There are still several multibillion dollar lawsuits pending. Even though the issue exists on the diesel-engine vehicles, the whole company has been affected. The settled and pending lawsuits are well into the multiple billions of dollars, but the lawsuits are the costs that can easily be seen. Volkswagen may never know the total monetary impact from loss of consumer confidence. This is an example where external failure costs often carry significant monetary impact that is difficult to fully encompass.

2.1.3 Cost of Quality Importance

The typical CoQ for a company ranges between 10%–50% of total sales (Dahlgaard & Dahlgaard, 2002; Gupta & Campbell, 1995; Juran & Godfrey, 1999; Sandoval-Chávez & Beruvides, 1998). The goal of a company should be to reduce the CoQ to a minimum. A low single percentage of the CoQ to total sales is ideal, yet only 40% of companies keep track of their quality costs (Gupta & Campbell, 1995). It costs less for a company to build a higher-quality product compared to fixing the problems associated with a lower-quality product (Bohan & Horney, 1991; Morse, 1993). Quality cannot be increased through inspection or appraisal methods. Often, a company may increase spending in appraisal methods which in turn reduces external failures but raises internal failures (Gupta & Campbell, 1995). The most cost-effective quality spending is in prevention, which can reduce failures exponentially (Cheah et al., 2011; Feiring et al., 1998). There is a "Rule of 10" in the CoQ stating that $1 in prevention cost reduces internal failure costs by $10 and external failure costs by $100 (Bohan & Horney, 1991).

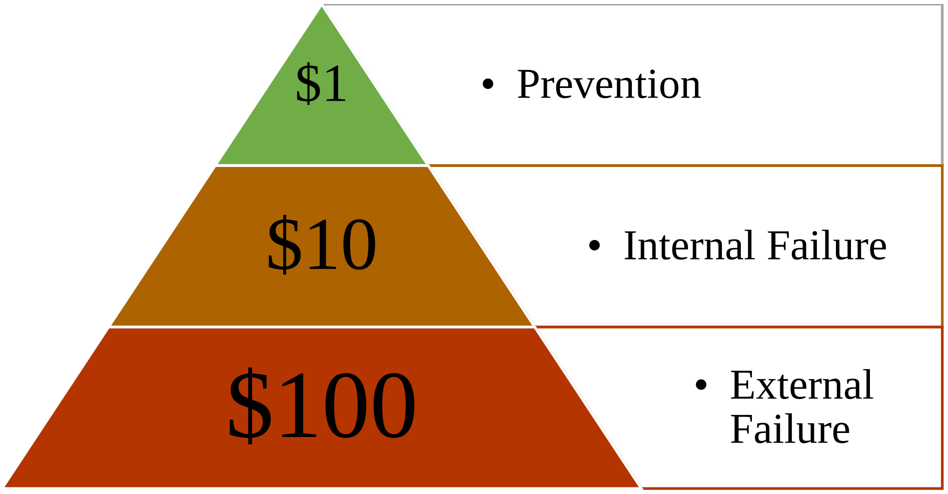


Figure 2-1. Rule of 10 quality costs.

A focus on prevention and investment in prevention techniques (e.g., FMEA) is needed to reduce failure. Reduced failure leads to decreased quality spending, which in turn increases profits and makes a company more competitive in the market place (Visawan & Tannock, 2004). When there is no product failure, internal costs and external costs are nonexistent (Juran & Godfrey, 1999).

2.2 Failure Mode and Effects Analysis

FMEA uses dependability analyses to identify failure modes, determine the effect of the failure modes, and rank the failure modes based on their effects. The ranking of the failure modes is used to show increasing risk. FMEA's goal is to improve reliability through corrective actions that decrease failure rate and its associated risk (Cassanelli, Mura, Fantini, Vanzi, & Plano, 2006).

2.2.1 Failure Mode and Effects Analysis History

The United Stated military created FMEA in the 1940s with the release of MIL-STD-1629, due in part to the large number of quality issues during World War II (United States Department of Defense, 1980). During the 1960s, NASA began to use FMEA to help reduce the number of failures in their Apollo rocket programs (H.-C. Liu et al., 2016). By the 1970s, the automotive industry started to use FMEA and helped to define the severity of effect, probability of occurrence, and likelihood of detection variables. The SOD variables are three ordinal numbers that are multiplied together to create the RPN (Hassan, Siadat, Dantan, & Martin, 2010). FMEA continued to evolve, and two distinct methods were created—design failure mode and effects analysis and process failure mode and effects analysis (Teng & Ho, 1996). Today, FMEA can be used in almost any industry (e.g., military, aerospace, automotive, medical, electronics, software, etc.) and is often tailored for the industry in which it is used (Carlson, 2012).

2.2.2 Failure Mode and Effects Analysis Use

An FMEA is used to “design out” future problems and to reduce and eliminate major problems (United States Department of Defense, 1980) on, for example, a process, product, software, or design. For the purposes of this paper, the term *product* will be used to define the multiple categories on which an FMEA can be performed. A wide variety of industries use FMEA (see Table 2-1), and researchers are adapting it for areas outside of traditional manufacturing including patient safety in healthcare (Sujan, Habli, Kelly, Pozzi, & Johnson, 2016), surgical training (Mesa, Hurtado, Margallo, Cabeza de Vaca, & Komorowski, 2015), transportation logistics (Stavrou & Ventikos, 2016), knowledge management (Luo & Lee, 2015), and environmental risk on wildlife habitats (Dargahi et al., 2016).

Table 2-1. Industries that use FMEA

Industry	Author
Aerospace	Freeman and Balas (2014); Guo et al. (2016); Jiang et al. (2016); Lillie, Sandborn, and Humphrey (2015)
Automotive	Aldridge, Taylor, and Dale (1991); Automotive Industry Action Group (2008); SAE International (2009); Whiteley, Dunnett, and Jackson (2016); Xu, Tang, Xie, Ho, and Zhu (2002)
Electronics	L.-Y. Chen and Yeh (2014); Jee, Tay, and Lim (2015); S.-F. Liu, Cheng, Lee, and Gau (2016)
Healthcare	S.-H. Chen (2016); Dağsuyu, Göçmen, Narlı, and Kokangül (2016); H.-C. Liu et al. (2016)
Manufacturing	Lolli, Gamberini, Rimini, and Pulga (2016); Pancholi and Bhatt (2016); Pandian (2010); Pradhan and Routroy (2014); Saleem et al. (2017); Sastri, Mongkolwana, and Feiring (2001)
Maritime	Akyuz, Akgun, and Celik (2016); Emovon, Norman, Murphy, and Pazouki (2015); Mentes and Ozen (2015); Pillay and Wang (2003); Zaman et al. (2014); Zhou and Thai (2016)
Military	Roy, Sarkar, and Mahanty (2016); United States Department of Defense (1980)
Power Plant	Bevilacqua, Braglia, and Gabbrielli (2000); Das Adhikary, Bose, Bose, and Mitra (2014)
Processing	Mariajayaprakash, Senthilvelan, and Gnanadass (2015); Pancholi and Bhatt (2016); Rezaee, Salimi, and Yousefi (2017)
Solar Cell	Colli (2015); Kuitche, Pan, and TamizhMani (2014)
Software	Goddard (2000); Park, Kim, and Lee (2014); Steinke, Kurniawati, and Nindel-Edwards (2010)
Transportation	Boufaied, Thabet, and Korbaa (2016); Zhu, Li, Xiao, and Xu (2015)
Wind Turbines	Arabian-Hoseynabadi, Oraee, and Tavner (2010); Fischer, Besnard, and Lina (2012); Shafiee and Dinmohammadi (2014)

2.2.3 Failure Mode and Effects Analysis Type

Over the years, there have been multiple versions of FMEAs introduced, with the two most common being design failure mode and effects analysis (DFMEA) and process failure mode and effects analysis (PFMEA). A DFMEA focuses on the design of a product; it is often used during the initial design of a product but can also be used at later stages of the life cycle when a user is looking for deficiencies in the design. A PFMEA focuses on the processing and manufacturing of a product and will look for deficiencies in the manufacturing process as well as for variability in the product components (Carlson, 2012). Table 2-2 lists additional types of FMEAs, their uses, and in what stage of the product life cycle they should be used.

Table 2-2. Types of FMEA

Type of FMEA	**Uses**	**When to use**
Concept FMEA	To evaluate concept alternatives prior to design activities	Conception/early life cycle
Design FMEA	At a subsystem or component level, to develop a design or when plan a major design change	Throughout life cycle
Failure modes, effects and criticality analysis (FMECA)	To add a detailed criticality analysis to an FMEA	Throughout life cycle
Maintenance FMEA	To determine maintenance approaches when the process/design is mature enough	After initial design/process developed
Process FMEA	To develop a new manufacturing process, to evaluate a major change in the process, when new technology becomes available	After initial design and throughout later life cycle
Software FMEA	Whenever the user determines there are risks to the software being utilized	After initial design
System FMEA	To develop a new system or plan a major change	Throughout life cycle

Note. Adapted from Carlson (2012).

The type of FMEA used is determined by the team executing it. Customers can require the frequency of the FMEA, but the producer benefits from performing an FMEA multiple times through the life cycle of a product to reduce deficiencies.

2.2.4 Failure Mode and Effects Analysis Procedure

The first step in performing an FMEA is to establish a multidisciplinary team whose members represent different groups in an industry environment. For a particular industry, this can include design engineers, process engineers, mechanical engineers, systems engineers, quality engineers, program managers, front line technicians, supply chain, manufacturing engineers, electrical engineers, and subject-matter experts for the product being reviewed. The team should be chosen based on relevant experience.

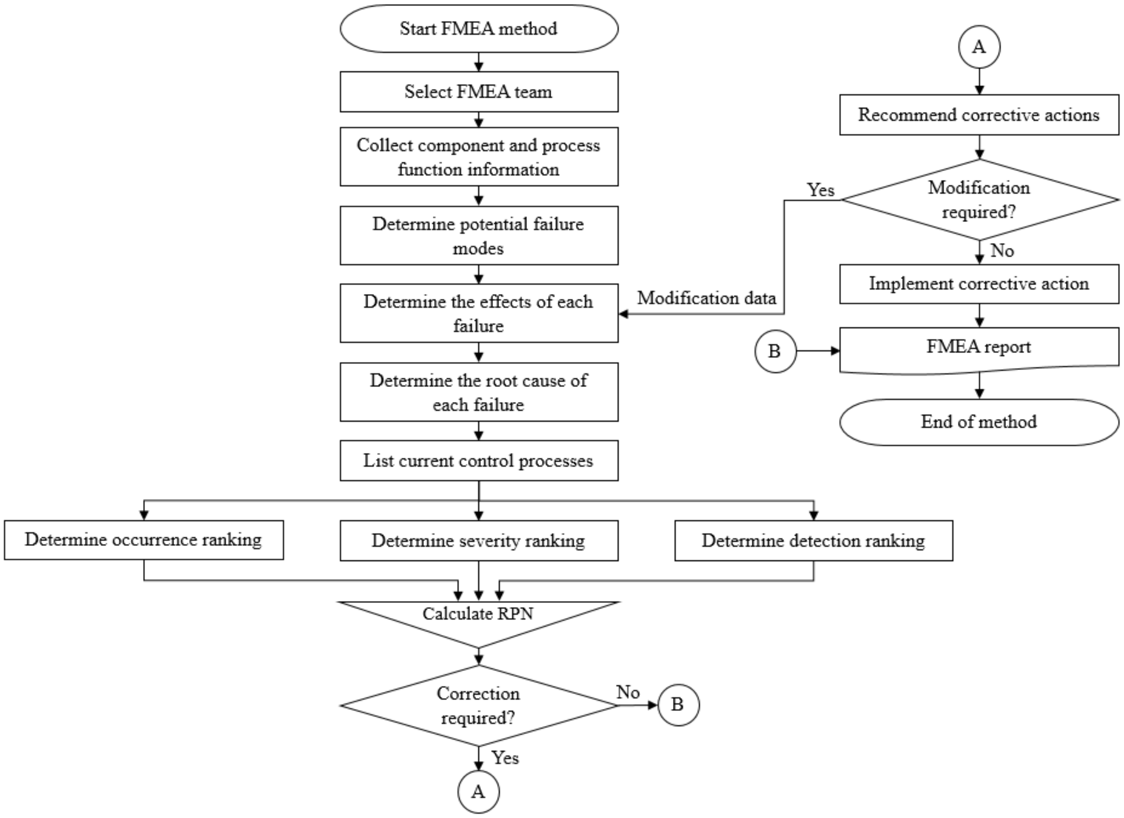
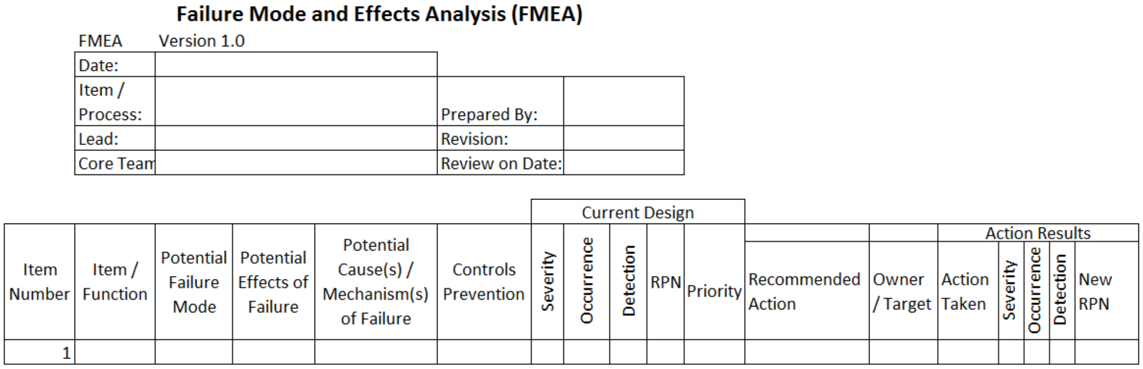


Figure 2-2. FMEA flowchart.

Note. Adapted from Rezaee et al. (2017).

The team begins by creating a preliminary risk assessment to determine areas of concern for the product. This helps identify where the team should focus their resources first. Once the team chooses an area of interest, they often perform block diagram(s). The block diagram is a visual map allowing the team to see interactions in a system that may be missed when only looking at the FMEA in spreadsheet format (e.g., Figure 2-3). With the block diagram complete, the team can now begin the FMEA process through population of the spreadsheet. The FMEA spreadsheet can be tailored for the industry, product, or system being evaluated. The order of the columns may change, but the categories are traditionally present.



Failure Mode and Effects Analysis (FMEA)

FMEA Version 1.0

Date:			
Item / Process:		Prepared By:	
Lead:		Revision:	
Core Team		Review on Date:	

						Current Design							Action Results				
Item Number	Item / Function	Potential Failure Mode	Potential Effects of Failure	Potential Cause(s) / Mechanism(s) of Failure	Controls Prevention	Severity	Occurrence	Detection	RPN	Priority	Recommended Action	Owner / Target	Action Taken	Severity	Occurrence	Detection	New RPN
1																	

Figure 2-3. Traditional FMEA spreadsheet example.

An FMEA normally uses a bottom-up approach (i.e., inductive) to look at individual components and at how failures at the component level can affect later subsystems and systems. At times, a team may use a top-down approach early in the life cycle when individual components are not fully defined. The FMEA spreadsheet helps organize an FMEA team's thoughts and provides a template for RPN calculations and priority ranking. The spreadsheet typically includes the following categories: item number, item/function, potential failure mode, potential effects of failure, potential cause/mechanism of failure, current controls/prevention, severity ranking, occurrence ranking, detection ranking, RPN, priority, recommended action, and owner of the action. Some FMEA spreadsheets also include columns for the implementation of a corrective action. These additional columns are labeled with the following: action taken, severity ranking, occurrence ranking, detection ranking, and new RPN.

FMEAs can be performed in different orders depending on team preference but are typically done by moving from row to row. The team begins by selecting an item to review. The user lists the item to be analyzed on the spreadsheet in the *Item/Function* column. The team then begins to brainstorm failure modes for that item and to list them in the *Potential Failure Modes* column. There can be multiple failure modes for an item being reviewed, and each failure mode should have its own row on the spreadsheet. The failure modes show how the product or system is deficient to its intended function as defined by the *Item/Function* column. Under *Potential Effects of Failure*, the FMEA team will list how the failure mode affects the function (e.g., decreased performance, customer dissatisfaction, etc.). The next step is to determine the potential cause or mechanism of failure. There can be multiple potential causes for a single failure mode, and each should be listed on its own row. Then, for each row of the spreadsheet, the team lists existing controls to detect or prevent the potential causes in the *Controls Prevention* column. The *Severity*, *Occurrence*, and *Detection* columns are the ordinal ranking factors used to measure the effect of failure. As discussed above, the SOD variables are subjective, the rankings for the SOD variables can be tailored, and ranking scales can be established by the team. Most times values are within 1 to 10, but some teams may use a scale of 1 to 5. Either scale can work, but the scales need to be the same for each variable to keep equal weighting. The SOD variables are independent of each other, with equal weighting. An uneven scale would give one of the variables a higher weighted value.

The severity of effect is a subjective measurement used to determine the severity of the failure effect. The ranking and severity effect definition is often tailored to the specific FMEA being performed, using linguistic terms. This allows the FMEA team to rank unique effects for the specific application. Table 2-3 shows an example of a severity-factor guideline with rankings. Severity is ranked from 1 to 10, with 10 being the most severe.

Table 2-3. Severity Factor Guideline

Severity of effect	**Severity ranking**
Product, end user, or plant safety at risk; risk of noncompliance to government regulations	**10**
Major impact on ability to produce quality product on time; includes significant interference with subsequent steps or damage to equipment; could result in mission failure	**9**
Product defect, rejection, failure in in-spec storage/operational environments; disruption to subsequent process steps	**7–8**
End-user dissatisfaction, some degradation in performance, loss of margin, or delays in the process	**4–6**
Slight end-user annoyance, slight deterioration in performance or margin, minor rework action, or in-line delays	**2–3**
Little to no effect on product or subsequent steps	**1**

Note. Adapted from Childs, Raheja, and Gullo (2012).

The occurrence factor is the probability of the failure mode occurring during the life cycle or being present during a process (Carlson, 2012). The rate at which the failure mode occurs is tailored to the FMEA being performed. Table 2-4 shows an example of an occurrence factor guideline. The occurrence is ranked from 1 to 10 with 10 being the most frequent occurrence.

Table 2-4. Occurrence Factor Guideline

Failure occurrence	**Probability of failure**		**Occurrence ranking**
	Defect rate	**Sigma**	
Failure is certain or almost inevitable	1 in 2		10
	1 in 8		9
Failure trend likely; process step not in statistical control or SPC not used; similar steps with known problems; little/no experience with new tool or step	1 in 20		8
	1 in 40		7
Possible failure trend; process in statistical control ($C_{PK} < 1.00$); similar steps with occasional problems	1 in 80		6
	1 in 400		5
	1 in 1,000	$\sim +3\sigma$	4
Low likelihood of failure; step in statistical control ($C_{PK} > 1.00$); similar steps with isolated occurrences	1 in 4,000	$\sim +3.5\sigma$	3
Very low likelihood of failure; in statistical control ($C_{PK} > 1.33$); rare occurrences in similar steps	1 in 20,000	$\sim +4\sigma$	2
Remote; no failure in similar steps ($C_{PK} > 1.67$)	1 in 1,000,000	$\sim +5\sigma$	1

Note. Adapted from Childs et al. (2012).

The likelihood-of-detection factor is how well the current processes or appraisal methods can detect if the failure mode is present prior to delivery to the end user. Table 2-5 shows an example of a likelihood-of-detection guideline. The likelihood of detection is ranked from 1 to 10, with a 10 denoting that current appraisal methods cannot detect a given failure mode.

Table 2-5. Detection Factor Guideline

Likelihood of detection	**Detection ranking**
No means of detection; no process or equipment to find problem in time to affect outcome	**10**
Controls would probably not detect defect; operator to perform self-inspection	**9**
Controls have poor chance of detecting defect; inspection alone to detect problem	**7–8**
Controls might detect defect; double inspection or inspection with equipment aids	**5–6**
Controls have good chance of detecting defect; process equipment detects presence of problem under most circumstances	**3–4**
Controls will almost certainly detect defect; process detects defects automatically	**1–2**

Note. Adapted from Childs et al. (2012).

The RPN is a numerical ranking that is the product of the three values of severity of effect, failure occurrence, and likelihood of detection.

Equation 2-2: Risk priority number.

$$RPN = S * O * D$$

$where\ S\ is\ the\ severity\ rank, O\ is\ the\ occurence\ rank, and\ D\ is\ the\ detection\ rank.$

The RPN denotes which failure mode has the largest effect or risk to the product. The higher the RPN, the larger the effect/risk on the product. The RPN is a prioritization metric for determining which failure modes should be addressed and where resources should be allocated. Some FMEA teams rank the RPN in descending numerical order to establish priority where others may choose to address failure modes with an RPN above a certain value (e.g., address failure modes for RPNs greater than 150). Both are acceptable methods for ranking risk during an FMEA.

The next portion of the FMEA process is to address the failure modes identified during analysis. Teams brainstorm corrective actions and implementation plans for high-risk failure modes defined by a large RPN. In the *Recommended Action* column, the FMEA team can list a corrective action. Corrective actions are chosen for the ability to reduce the failure effect, denoted by RPN, on the product. In the *Owner/Target* column, actions are delegated to an individual or group responsible for addressing the failure mode. A target due date is also listed for an implementation action. The *Action Taken* column lists the corrective action implemented for the given failure mode. The post SOD variables and RPN columns are used with respect to the corrective action being implemented. After taking corrective action the FMEA team compares the new RPN with the original RPN to look for improvement in the failure mode. Improvement is indicated through a lowered RPN number (e.g., original RPN 300 to a new RPN of 150). Thus, teams want to minimize the RPN number.

The FMEA is not complete after filling out the FMEA spreadsheet. The team also needs to monitor progress on implementation and evaluate if the changes improve the product. The FMEA process relies on participation, follow through, and execution by the entire team.

2.2.5 Failure Mode and Effects Analysis Limitations

Failure mode and effects analysis has been in use since World War II. Since then, there have been improvements and variations in the process, as well as numerous documented limitations. H.-C. Liu et al. (2013) performed an in-depth literature review on alternative FMEA methods from 1992 through 2012, focusing on peer-reviewed journal articles, and found 75 different studies. Throughout this time frame, they found the number of studies published increased in every 4-year period (Figure 2-4). Liu et al. hypothesized the trend would continue to increase as more users were looking for a practical method to improve the FMEA process. The researchers identified 40 studies published between 2007 and 2011; now, a search for alternative FMEA methods yields hundreds of studies from the past 5 years. The following sections provide a sampling of these methods and groups them into the major themes found in the literature.

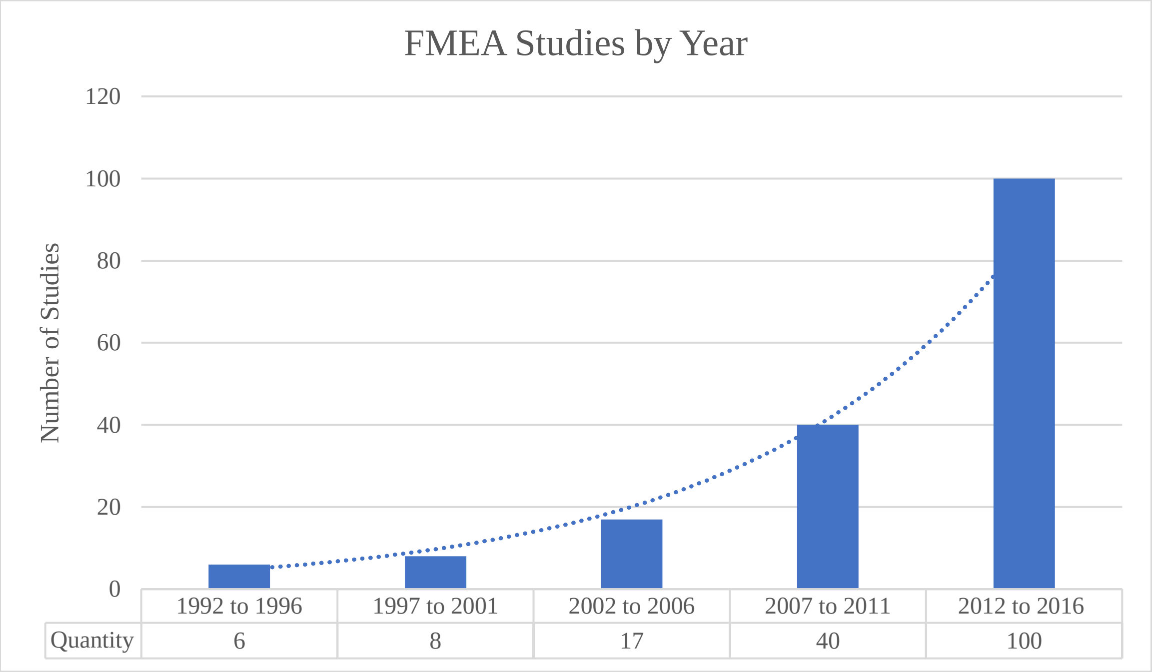


Figure 2-4. FMEA studies by year.

Note. Adapted from H.-C. Liu et al. (2013).

2.2.5.1 Time to Perform

A full FMEA is a time-consuming process (Bluvband & Grabov, 2009; Carmignani, 2009; Goble, 2012; Kmenta, 2001; Price & Taylor, 2002). This can create a challenge for the user to complete the process and can make the process cost prohibitive (Carmignani, 2009). Goble (2012) states, “solving the problem is not part of the analysis; the problems are solved once the analysis has been completed” (p. 20). There have been attempts to reduce the time to complete an FMEA. Price and Taylor (2002) created an automation process to reduce the amount of time to perform FMEA and to prioritize the results, reducing the time to evaluate the failure scenarios. Arabian-

Hoseynabadi et al. (2010) evaluated commercially available software (i.e., Reliasoft Xfema, Reliability Workbench 10.1, and Reliability Studio 2007 V2) to reduce the time to perform an FMEA. Ebrahimipour, Rezaie, and Shokravi (2010) suggested the use of a database with common themes from previous studies that a team could reference during FMEA.

2.2.5.2 When to Use Failure Mode and Effects Analysis

FMEA is commonly used too late in the life cycle to make an impact on a product (Aldridge et al., 1991; Kmenta, 2001; United States Department of Defense, 1980). An FMEA is an iterative process and should be used throughout the life cycle of a product (Cassanelli et al., 2006), but it is important to implement it as early in the design as possible (Kmenta, 2001; Teng & Ho, 1996; United States Department of Defense, 1980). As discussed earlier, quality can only be designed into a product and cannot be inspected in (Childs et al., 2012). Use of FMEA during the initial design allows future problems to be identified, reduced, or eliminated and significantly decreases the chances of major and catastrophic failures (United States Department of Defense, 1980). The design phase of a product accounts for most of the life-cycle cost. At the end of the design phase, 75% of the life-cycle cost has been committed to the product while only 15% of the actual life-cycle cost has been spent, as shown in Figure 2-5 (SAE International, 1992).

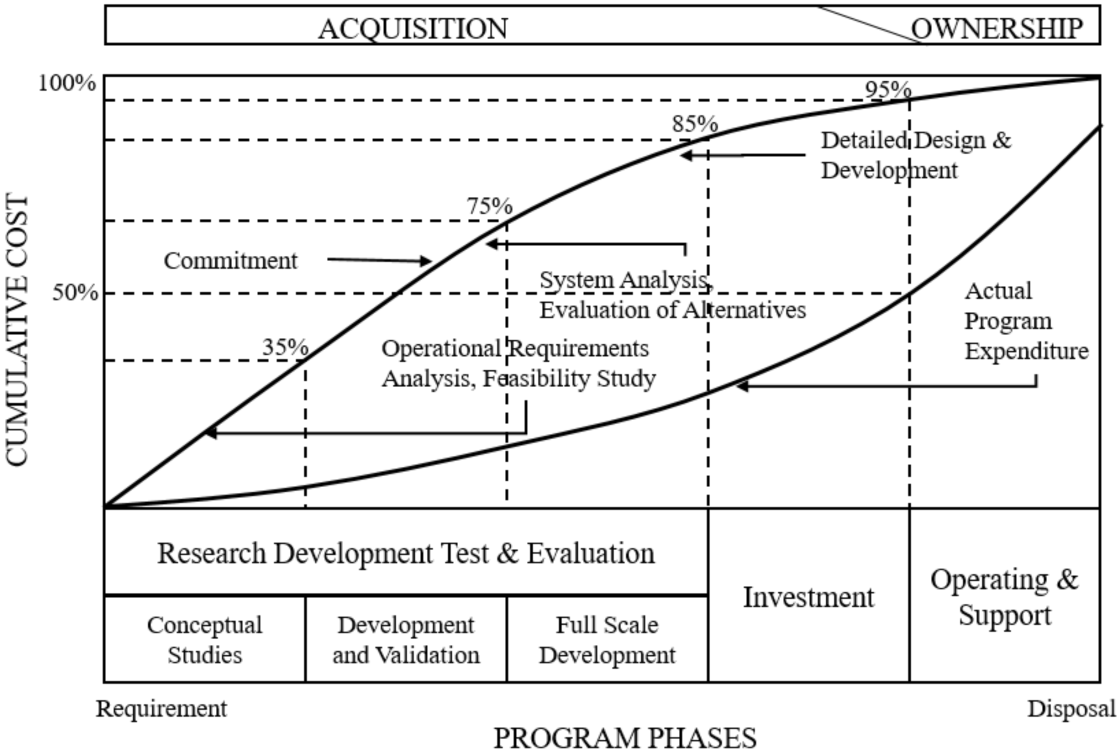


Figure 2-5. Life-cycle cost committed at different program phases.

Note. Adapted from SAE International (1992).

2.2.5.3 Ambiguity of the RPN

One of the main arguments against FMEA is the ambiguity of the RPN (J. Bowles, 2004; Gargama & Chaturvedi, 2011; Kmenta & Ishii, 2005; H.-C. Liu et al., 2016; Lolli et al., 2016; Pillay & Wang, 2003; Ravi Sankar & Prabhu, 2001; Rhee, 2005). The RPN is made of the three ordinal values for severity of effect, probability of occurrence, and likelihood of detection. An ordinal value shows the rank, but the interval between values can vary (J. Bowles, 2004; Rhee & Ishii, 2003). Taking the product of an ordinal number results in losing the rank and performing an invalid mathematical transformation (J. Bowles, 2004; Kmenta, 2001; H.-C. Liu et al., 2016; Mentes & Ozen, 2015; Rhee & Ishii, 2003). The following sections provide more details on RPN ambiguity, including subjectivity of the SOD variables and criticism of the RPN values.

2.2.5.3.1 Subjectivity of the Severity, Occurrence, and Detection Variables

The nature of the FMEA leads to subjectivity of the SOD variables. As shown in Table 2-1, many industries use FMEA, including the automotive, aerospace, healthcare, transportation, manufacturing, military, and process industries. Their FMEA teams create the SOD variable scales and rankings based on their industries. While certain scales may be usable in similar industries, the linguistic nature of the variables does not universally translate.

The severity of effect is the measurement of the effect of a failure occurring. Table 2-6 shows severity-of-effects rankings for a generic industry, automotive industry, and blow mold manufacturing. As seen in the table, a severity ranking of 7 can have different meanings. Some users choose linguistic terms like those in the first column for measuring severity. These terms are highly subjective and may not reproduce the same values for different FMEA teams.

Table 2-6. Severity of Effects, by Industry

Linguistic terms (from Automotive Industry Action Group (2008)	Generic industry (from Childs et al. (2012)	Automotive (from Automotive Industry Action Group (2008)	Blow-mold manufacturing (from Lolli et al. (2016)	Severity
Hazardous without warning	Product, end user, or plant safety at risk; risk of noncompliance to government regulations	Very high severity ranking, when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning	Damage to customers	**10**
Hazardous with warning	Major impact on ability to produce quality product on time; includes significant interference with subsequent steps or damage to equipment; could result in mission failure	Very high severity ranking, when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning	Damage to retailers	**9**
Very high	Product defect, rejection, failure in in-spec storage/operational environments; disruption to subsequent process steps	Vehicle/item inoperable, with loss of primary function.	Very frequent line stops, leading to the blocking of production	**8**
High		Vehicle/item operable but at reduced level of performance. Customer dissatisfied.	Repeated line stops, leading to the blocking of production	**7**
Moderate	End-user dissatisfaction, some degradation in performance, loss of margin, or delays in the process	Vehicle/item operable, but comfort/convenience item(s) inoperable. Customer experiences discomfort.	Very frequent line stops, leading to the product's selection	**6**
Low		Vehicle/item operable, but comfort/convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction.	Repeated line stops, leading to the product's selection	**5**
Very low		Fit & finish/squeak & rattle item does not conform. Defect noticed by most customers.	Periodic problems of machinability	**4**
Minor	Slight end-user annoyance, slight deterioration in performance or margin, minor rework action or in-line delays	Fit & finish/squeak & rattle item does not conform. Defect noticed by average customer.	Sporadic problems of machinability	**3**
Very minor		Fit & finish/squeak & rattle item does not conform. Defect noticed by discriminating customer.	Rare problems of machinability	**2**
None	Little to no effect on product or subsequent steps	No effect	The line does not stop without damaging customers/retailers	**1**

The probability of occurrence is the probability that the failure occurs. Table 2-7 shows the probability of occurrence for a generic industry, automotive industry, and marine industry. The probabilities for each industry vary, where a probability of occurrence of 1 in 20 could be a 7 or 8, or 1 in 1,000 could be 4 or 5. Figure 2-6 is a plot on a logarithmic scale of the varying probabilities of occurrence. Later sections of this paper discuss how the rankings influence RPN calculations.

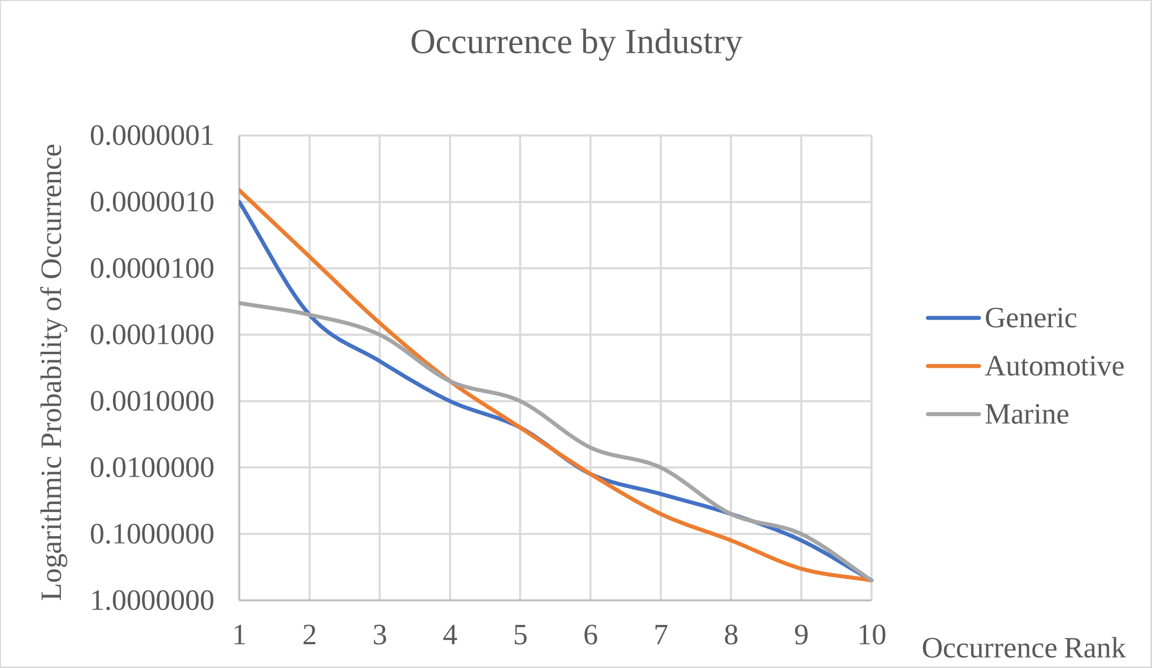


Figure 2-6. Occurrence by industry scale.

Table 2-7. Probability of Occurrence, by Industry

Linguistic terms (from Automotive Industry Action Group (2008)	**Generic industry (from Childs et al. (2012)**	**Automotive (from Automotive Industry Action Group (2008)**	**Marine (from Pillay and Wang (2003)**	**Occurrence**
Very High: Failure is almost inevitable	1 in 2	≥ 1 in 2	1 in 2	**10**
	1 in 8	1 in 3	1 in 10	**9**
High: Repeated failures	1 in 20	1 in 8	1 in 20	**8**
	1 in 40	1 in 20	1 in 100	**7**
Moderate: Occasional failures	1 in 80	1 in 80	1 in 200	**6**
	1 in 400	1 in 400	1 in 1,000	**5**
	1 in 1,000	1 in 2,000	1 in 2,000	**4**
Low: Relatively few failures	1 in 4,000	1 in 15,000	1 in 10,000	**3**
	1 in 20,000	1 in 150,000	1 in 20,000	**2**
Remote: Failure is unlikely	1 in 1,000,000	≤ 1 in 1,500,000	≤ 1 in 20,000	**1**

The likelihood of detection is the measure of current process controls or tests being able to identify the failure prior to leaving the manufacturing facility. Table 2-8 shows the likelihood of detection for a generic industry, automotive industry, and blow-mold manufacturing. The linguistic variable for detection has been tailored for each industry and shows the subjectivity.

Table 2-8. Likelihood of Detection, by Industry

Linguistic terms (from Automotive Industry Action Group (2008)	Generic industry (from Childs et al. (2012)	Automotive (from Automotive Industry Action Group (2008)	Blow-mold manufacturing (from Lolli et al. (2016)	Detection
Absolute Uncertainty	No means of detection; no process or equipment to find problem in time to affect outcome	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control.	No identifying test	**10**
Very Remote	Controls would probably not detect defect of failure; operator to perform self-inspection	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and a highly skilled technician can perform it using dedicated tools	**9**
Remote	Controls have poor chance of detecting defect; inspection alone to detect problem	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and an expert, highly skilled technician can perform it	**8**
Very Low		Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and a fairly skilled operator can perform it using dedicated tools	**7**
Low	Controls might detect defect; double inspection or inspection with equipment aids	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and a fairly skilled operator can perform it	**6**
Moderate		Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and it’s easy to identify the failure using dedicated tools	**5**
Moderately High	Controls have good chance of detecting defect; process equipment detects presence of problem under most circumstances	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and it’s easy to identify the failure	**4**
High		High chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and the failure is immediately found using dedicated tools	**3**
Very High	Control will almost certainly detect defect; process detects defects automatically	Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode	A visual test exists, and the failure is immediately found	**2**
Almost Certain		Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode	Automatic test	**1**

2.2.5.3.2 Risk Priority Number Criticism

Multiplying the three SOD variables produces the RPN as well as large gaps in the RPN values. The SOD rankings are from 1 to 10, making the lowest RPN value equal to 1 (i.e., 1*1*1=1) and the highest RPN value equal to 1,000 (i.e., 10*10*10=1,000). Many of the numbers in the 1 to 1,000 scale are not achievable. There are only 120 individual RPN values that can occur, so 88% of the numbers within 1 to 1,000 are not achievable. When the values of the RPN are graphed as a histogram (Figure 2-7), the large gaps between RPN values along the scale are clear. Most RPN values are well below 500, with only 6% above 500. The average RPN value is 166.4 while the median is 105. There are only 6 RPN values that can be formed by a unique set of SOD variables, yet RPNs 60, 72, and 120 can be formed 24 different ways (J. Bowles, 2004). The multiple replications lead to the low number of achievable RPN values.

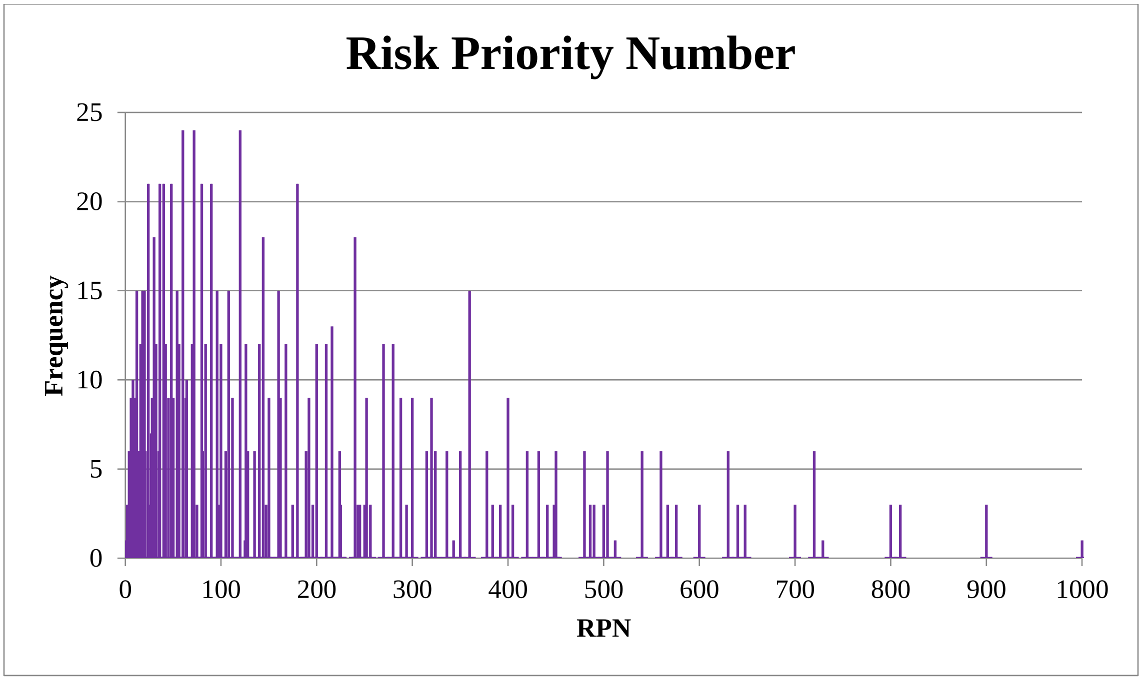


Figure 2-7. RPN histogram showing the frequency of occurrence for individual RPN.

Note. Adapted from J. Bowles (2004).

The high frequency of similar RPN values makes prioritization difficult because a similar RPN value shows no difference in the failure effect (L.-Y. Chen & Yeh, 2014). Many researchers identify the varying severities denoted from a common RPN value as a shortcoming of traditional FMEA (Gilchrist, 1993; Mentes & Ozen, 2015; Pillay & Wang, 2003; Rhee, 2005; Sawhney, Subburaman, Sonntag, Rao, & Capizzi, 2010; Xiao, Huang, Li, He, & Jin, 2011). For example, Table 2-9 shows all the combinations of SOD variables that result in an RPN value of 150. As seen in Table 2-3, a severity of 3 equates to *Slight end-user annoyance, slight deterioration in the performance or margin*, and a severity of 10 equates to *product, end user, or plant safety at risk*. The RPN value shows no difference between end users being annoyed compared to their safety being at risk from a product. For example, in the case of a passenger on an airliner, a severity of 3 may be assigned to a chair that does not properly recline. A severity of 10 may be assigned to the oxygen bag not deploying during depressurization, depriving the passenger of oxygen. Thus, a common RPN can mask the increased urgency of a problem (Pillay & Wang, 2003).

Table 2-9. Possible SOD Combinations for RPN of 150

Severity	Occurrence	Detection	RPN
3	5	10	150
3	10	5	150
5	3	10	150
5	5	6	150
5	6	5	150
5	10	3	150
6	5	5	150
10	3	5	150
10	5	3	150

There are also large gaps in the scale, creating difficulty in ranking the RPN value. There are 880 RPN values which are not achievable; therefore, it is difficult to determine the degree of improvement for an implemented change. An RPN reduction from 700 to 648 is the same scale reduction as from 81 to 80, based on achievable numbers. Table 2-10 shows a sample of RPN value gaps from an RPN value and the next achievable RPN value. In some cases, these gaps can be as large as 100. The RPN value becomes more ambiguous when looking at the actual SOD variable values. For example, an RPN value of 81 could have SOD = 9,1,9 and SOD = 9,3,3. If there is an increase in occurrence by 1, along with a decrease of 1 in both severity and detection, the new RPN values would be 128 (SOD = 8,2,8) and 64 (SOD = 8,4,2). With the same changes made to both initial RPN values of 81, one decreases to 64 while the other increased to 128. Based on the new RPN values, one failure mode is now double the RPN value of the other failure mode.

Table 2-10. Sample Gaps in RPN Value Scale

RPN value	**Next achievable RPN value**	**Gap**
50	54	4
80	81	1
90	96	6
96	98	2
100	105	5
180	189	9
200	210	10
250	252	2
252	256	4
256	270	14
450	480	30
480	486	6
640	648	8
648	700	52
800	810	10
810	900	90
900	1000	100

During an in-depth review of alternative FMEA processes, H.-C. Liu et al. (2013) grouped the number of occurrences for common complaints with ambiguity of the RPN value, as shown in Table 2-11. The common themes identified by H.-C. Liu et al. (2013) are also identified in this literature review.

Table 2-11. Common Themes in RPN Value Ambiguity

Ambiguity of RPN value	Number of Studies
Relative importance among SOD variables is not taken into consideration	45
Different combinations of SOD variables produce the same RPN value, but risk may be different	33
SOD variables are subjective and difficult to determine	21
RPN multiplication is an incorrect mathematical operation	14
RPN value cannot be used to measure the effectiveness of corrective actions	12
Large gaps in RPN values make it difficult to determine the impact of corrective actions due to holes	10

Note. Adapted from H.-C. Liu et al. (2013).

2.2.6 Attempts to Address RPN Ambiguity

There have been multiple attempts to address the ambiguity of the RPN value. Select attempts include the addition of weighting factors to the RPN formula (Ben-Daya & Raouf, 1996; Bevilacqua et al., 2000; Xiao et al., 2011), changes to the RPN formula (Li & Zeng, 2016; Sawhney et al., 2010), and creation of a new prioritization metric. H.-C. Liu et al. (2013) discovered the top three attempts for creation of a new prioritization metric are through fuzzy-based analysis, grey theory, and a cost-based metric. The following sections describe the different methods that have been proposed in the literature and critique their ability to address the ambiguity of the RPN value.

2.2.6.1 Fuzzy Theory and Grey Theory

Fuzzy logic systems can help address uncertainty in a calculation or system. When applied to FMEA, the fuzzy inference system, the most popular, is described as having three main elements: fuzzification, fuzzy inference, and defuzzification (H.-C. Liu et al., 2013). The fuzzification is the creation of overlapping linguistic terms to cover the full range of a system (Garrido, 2012). The linguistic terms, applied by the FMEA team to the SOD variables, are meant to reduce the subjectivity of the SOD-variable inputs from the individual FMEA team members. For example, a set of linguistic terms may be *Very High*, *High*, *Moderate*, *Low*, and *Very Low*. These terms are called fuzzy modifiers and are set up so they are neither entirely true nor entirely false (Garrido, 2012). The next portion involves the fuzzy inference, which is done through the creation of fuzzy "If-Then" rule sets for measuring risk based on the linguistic terms. The final step is the defuzzification of the data, which yields a risk number used for prioritization (H.-C. Liu et al., 2013). This risk number is the replacement for the RPN value.

Grey number theory is a method that allows evaluation of uncertain decisions in a practical application (Pancholi & Bhatt, 2016). It is based on making a decision when the information is incomplete or when portions are missing. Grey theory uses intervals where the upper limits and lower limits are not known, called grey numbers, as well as an interval in the middle with known values called white numbers (Pancholi & Bhatt, 2016).

2.2.6.1.1 Fuzzy-Based Studies

L.-Y. Chen and Yeh (2014) perform an evaluation of three alternative RPN-value calculations. The first alternative is a two-factor sort where the RPN value is calculated by multiplying the severity and occurrence rankings. The second alternative uses a simple sort method. In this calculation, the severity becomes the hundredth digit, the occurrence becomes the tenths digit, and detection becomes the unit digit. The final method uses a fuzzy method that calculates the fuzzy values for detection and severity and replaces the occurrence ranking with the process capability (C_{pk}). The fuzzy RPN value is the product of the fuzzy severity, fuzzy detection, and the C_{pk}. Table 13 presents a comparison using a wafer manufacturing process on the three alternatives and the traditional RPN value calculation. Chen and Yeh have found that traditional RPN values, two-factor-sort RPN values, and simple-sort RPN values produce similar numbers for the failures modes and make the sequence ambiguous. The fuzzy RPN value creates many more unique values. Out of the 28 combinations evaluated, traditional RPNs have 12 unique numbers, two-factor-sort RPNs have 8 unique numbers, simple-sort RPNs have 17 unique numbers, and fuzzy RPNs have 28 unique numbers.

Table 2-12. RPN-Value Analyses in a Wafer Manufacturing Process

Failure factor	**Traditional RPN**		**Two-factor sort RPN**		**Simple sort RPN**		**Fuzzy RPN**	
	Value	**Sequence**	**Value**	**Sequence**	**Value**	**Sequence**	**Value**	**Sequence**
A11	45	8	15	5	533	13	82.8	23
B11	84	1	28	1	743	1	168.38	3
B12	42	9	14	6	723	2	113.84	14
C11	72	3	18	4	634	5	162.24	4
C12	36	11	12	7	623	9	155.74	5
D11	72	3	18	4	634	5	109.01	18
D12	48	7	12	7	624	8	93.56	22
E11	72	3	24	2	634	3	135.92	8
F11	45	8	15	5	533	13	183.42	2
F12	40	10	20	3	542	12	136.1	7
G11	80	2	10	8	544	10	114.83	13
G12	40	10	15	5	542	12	78.28	26
H11	60	4	12	7	625	7	48.04	28
H12	54	5	18	4	633	6	59.24	27
I11	30	12	10	8	523	16	120.86	11
I12	30	12	15	5	532	14	129.22	9
I13	40	10	20	3	542	12	111.11	15
I14	60	4	20	3	543	11	81.78	24
J11	72	3	18	4	634	5	229.72	1
J12	48	7	12	7	624	8	144.75	6
K11	48	7	12	7	434	17	123.5	10
L11	72	3	24	2	643	3	110.26	16
L12	48	7	24	2	642	4	109.24	17
L13	72	3	18	4	634	5	117.95	12
M11	60	4	20	3	543	11	107.11	19
M12	80	2	20	3	544	10	80.82	25
M13	50	6	10	8	525	15	104.27	20
N11	60	4	12	7	625	7	100.3	21

Note. Adapted from L.-Y. Chen and Yeh (2014).

Aikhuele and Turan (2016) seek to make it easier to leverage historical information during a product redesign by using *intuitionistic fuzzy-logic technique for order by similarity to ideal solution* (IF-TOPSIS) method. This method is used during multicriteria decision-making, which is an analysis like FMEA. The method starts with the FMEA team reviewing the past data and creating a list of product components that fit the targeted parameters (e.g., high failure rates or low system availability). The team then looks at the SOD variables in linguistic terms. For example, probability of occurrence may be *Very High*, *High*, *Moderate*, *Low*, or *Very Low*. The values from the linguistic terms are combined and modified using a weight vector that creates the inputs for the fuzzy matrix. This matrix transforms the data into the exponential-related matrix. The closeness coefficient is derived from the matrix, which shows the optimal solution for rank, where a lower closeness coefficient number is desired. The authors compare four different IF-TOPSIS versions along with traditional RPN (Table 14). The results show a general agreement in ranking between the IF-TOPSIS methods, with an approximately 70% agreement with traditional RPN ranking methods. The authors state the advantages over traditional RPN include the ability to model the indecisiveness of the FMEA team during the subjective assessments, and failure detection becomes more objective with the IF-TOPSIS method.

Table 2-13. Failure Ranking in IF-TOPSIS vs. RPN

Product components	New fuzzy model	Fuzzy TOPSIS model	IWF-TOPSIS	IFH-TOPSIS	RPN Method
PM1	4	9	10	7	6
PM2	6	13	8	9	10
PM3	13	4	5	5	9
PM4	5	6	2	6	3
PM5	11	11	11	11	14
PM6	10	15	14	15	10
PM7	15	16	16	16	15
PM8	7	2	15	4	13
PM9	14	7	3	8	8
PM10	1	1	1	1	1
PM11	8	10	13	10	6
PM12	3	3	4	3	4
PM13	2	5	7	2	2
PM14	12	14	12	14	10
PM15	16	10	9	13	16
PM16	9	15	6	12	5

Note. Adapted from Aikhuele and Turan (2016).

2.2.6.1.2 Grey-Theory Studies

Pancholi and Bhatt (2016) use a multicriteria decision-making approach in an aluminum extruding plant to evaluate risks and failure modes and, in the process, help implement a maintenance schedule. They start with the traditional SOD variables and add maintenance variables including economic cost, spare parts, maintainability, and economic safety. Grey-complex proportional assessment method (COPRAS-G) is used to evaluate the different variables by creating a set of linguistic grey numbers for the variables. Pancholi and Bhatt follow a methodology based on COPRAS-G to create a prioritization metric they call “maintainability criticality index”. This is done by creating a decision matrix with criteria ranking in grey intervals. The decision matrix is then normalized, and the weight of each decision criteria is established. The next step is to calculate the relative significance through the maintainability criticality index. The final ranking is based on maintainability criticality index and highlights the largest risk in the system.

Razi, Danaei, Ehsani, and Dolati (2013), evaluating the risk factors of a computer numerical control (CNC) machining process, propose a grey-theory-based FMEA for determining the largest risk factors. The first step is to determine the potential failures modes with respect to a CNC machine. The authors then create a set of linguistic terms for measuring the SOD variables. The FMEA team uses the linguistic terms to assess the severity, probability of occurrence, and likelihood of detection for each of the identified failure modes. The FMEA team then converts the rankings to a grey matrix, normalize the grey-matrix values, and cluster them to give a ranking of the highest risk factors in the system.

2.2.6.1.3 Mixed-Method Studies

Pillay and Wang (2003) find similar RPN values could mask increased urgency in a problem. The focus of their research is evaluating risk when the RPN value is the same. The authors use a fuzzy logic system to create 125 If-Then rule sets. They then reduce the amount of rule sets by combining similar rules, resulting in 35 If-Then rules. This reduced rule set is used with a linguistic variable term set (*Remote*, *Low*, *Moderate*, *High*, *Very High*) for the SOD variables. A defuzzified ranking is created to generate the risk and fuzzy risk priority number (FRPN) values. The authors also use grey theory along with fuzzy variables as an alternative approach. In a case study on a fishing vessel, traditional FMEA, fuzzy-based FMEA, and grey-theory FMEA all produced varying rankings, showing each method ranked risk differently (Pillay and Wang

(2003). Overall, all three methods produce the same top-three failure modes. The research thus shows that similar RPN values can denote varying risk.

Zhou and Thai (2016) use both fuzzy logic and grey theory to replace the RPN value. They compare the two methods, where fuzzy logic creates the FRPN and grey theory creates the grey relational coefficient, using a case study for oil-tanker-equipment maintenance and failure. First, the FMEA team must create a fuzzy number set to be assigned to the linguistic terms for the SOD variables. The team then brainstorms failure modes and individually ranks each of the failure modes, using the fuzzy numbers for the SOD linguistic terms. An aggregate of the FMEA team's response is used along with a weighting factor for importance. The weighted aggregate values for the individual SOD variables use alpha-level sets to give the FRPN. Next, a defuzzification is performed using the centroid defuzzification method to give the final FRPN value used for ranking.

For the grey theory calculation, Zhou and Thai (2016) start with the same fuzzy linguistic terms for the SOD variables. The SOD variables are then defuzzified according to the membership function, and a crisp number is calculated. The grey relational coefficient is calculated, and weights are introduced to determine the degree of relation between potential causes and failures. In the grey relation method, a smaller relational coefficient denotes higher risks. In the case study on oil-tanker equipment used by a global shipping company, Zhou and Thai (2016) find 17 different failure modes. The priority rankings between the fuzzy theory and grey theory methods are nearly identical (Table 2-14).

Table 2-14. Grey Theory vs. FRPN

Failure number	Failure mode	Grey relational coefficient	Grey ranking	FRPN	FRPN ranking
1	Auxiliary engine	0.55	8	4.44	8
2	Auxiliary machinery	0.54	6	4.57	6
3	Boiler	0.54	7	4.52	7
4	Cargo pump	0.73	14	2.73	14
5	Cargo system	0.84	17	2.03	17
6	Desk machinery	0.50	3	5.24	3
7	Electrical	0.61	11	3.74	10
8	Emergency equipment	0.66	12	3.18	12
9	Hull part	0.77	15	2.42	15
10	Hydraulic system	0.68	13	3.04	13
11	Inert gas system	0.61	10	3.67	11
12	Main engine	0.38	1	8.07	1
13	Monitoring system	0.51	4	5.09	4
14	Mooring	0.57	9	4.28	9
15	Navigation equipment	0.42	2	6.96	2
16	Piping system	0.53	5	4.66	5
17	Steering gear	0.79	16	2.26	16

Note. Adapted from Zhou and Thai (2016).

2.2.6.1.4 Fuzzy Theory and Grey Theory Evaluation and Limitations

Fuzzy theory and grey theory are attempts to address the ambiguity of the RPN value by replacing it with an alternative prioritization metric; fuzzy theory uses FRPN while grey theory uses grey relational coefficient. The above studies demonstrate how fuzzy and grey theory can account for uncertainty and subjectivity of the traditional RPN method. Membership functions are used in fuzzy analysis and grey theory to help reduce uncertainty found in the generation of traditional RPN values (Zhou & Thai, 2016). Both methods show that a common RPN value can mask enhanced risk and can reduce the number of common RPN values during an analysis (Aikhuele & Turan, 2016; L.-Y. Chen & Yeh, 2014; Pillay & Wang, 2003).

Fuzzy theory and grey theory are not without their limitations. Like the traditional RPN value, FRPN and the grey correlation coefficient cannot be compared to other studies. The rankings are on an interval scale. An FRPN of 200 is twice that of an FRPN of 100, but this does not mean that the failure mode is twice the risk. H.-C. Liu et al. (2013) list the following limitations to these methods: Creation of the fuzzy If-Then rule sets and membership functions are time consuming and expensive, If-Then rule statements that result in similar consequence but have different input values cannot be distinguished, and complex calculations are difficult to perform and can result in information loss. The authors also list the following limitations of attempts to reduce the amount of If-Then rule sets and membership functions: Rule sets that have similar consequences with different input values are indistinguishable (i.e., there is no observable difference between failure modes); FMEA team members have different judgments, so rule set reduction can become inconsistent; and reduced rule sets are incomplete sets.

The SOD variable used in fuzzy theory and grey theory is an underlying weakness of the traditional FMEA that is not addressed by these methods.

2.2.6.2 Cost-Based FMEA

FMEA is a dependability analysis method that is used to prevent failure cost in the CoQ. A common theme identified during the literature review is the lack of a costing element in the RPN prioritization metric (Childs et al., 2012; Dong, 2007; Gilchrist, 1993; Kmenta & Ishii, 2005; Pandian, 2010; Rahimi, Jamshidi, Ait-Kadi, & Ruiz, 2015; Rhee, 2005; Rhee & Ishii, 2003;

Tarum, 2001; von Ahsen, 2008). Cost is a universal measure of consequence and can measure the severity of an occurrence (Kmenta & Ishii, 2005).

2.2.6.2.1 Cost-Based FMEA Studies

The concept of a cost-based prioritization metric is first introduced by Gilchrist (1993), who questions the multiplication of the three SOD variables and notes they are non-linear and should not be multiplied or added. Gilchrist proposes using expected cost as the prioritization metric. This would allow for a universal number across FMEAs that could be compared with other studies. The expected cost would be used to determine the likelihood of a customer receiving a defective unit.

Equation 2-3: Expected cost (Gilchrist (1993).

$$EC = C * n * Pf * Pd$$

where EC is the expected cost, C is the cost of a failure occurring, n is the number of products being built, Pf is the probability of a failure occurring, and Pd is the probability of a failure reaching the customer.

Gilchrist states probability is an appropriate measure of chance of occurrence, and cost is an appropriate measure of severity.

Kmenta (2001) expands on Gilchrist’s early idea by introducing the concept of failure scenario cost-based FMEA. Failure scenarios are the total effect of a failure introduction (cause) to the failure discovery (effect) and include the intermediate effects along the path. Kmenta uses an example of brake failure to show the different scenarios that could occur (Figure 2-8). Given 6 initial causes and 2 end effects, there is a total of 12 different brake-failure scenarios.

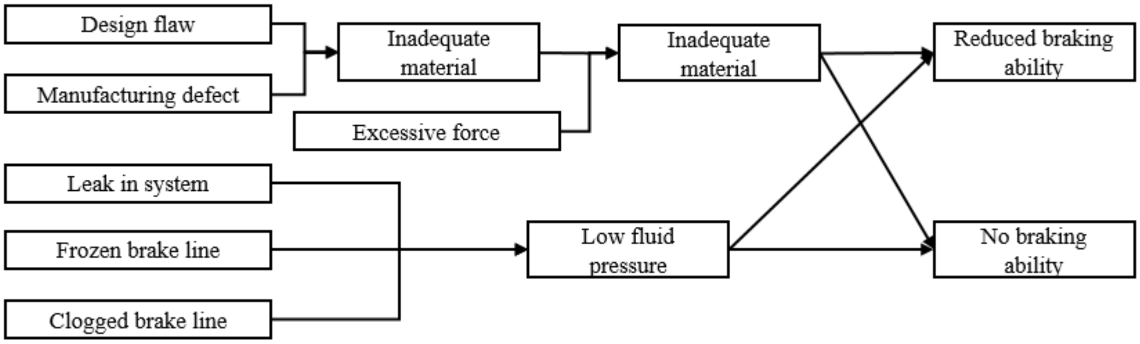


Figure 2-8. Failure scenarios for brake failure.

Note. Adapted from Kmenta (2001).

For a given failure scenario, the effect may be caught during prototype testing or discovered by the end user. The probability for the different cause and effects during a product's life cycle is shown in Figure 2-9, where the probability of an individual failure is the product of the probability of the failure occurring and the probability of the end effect.

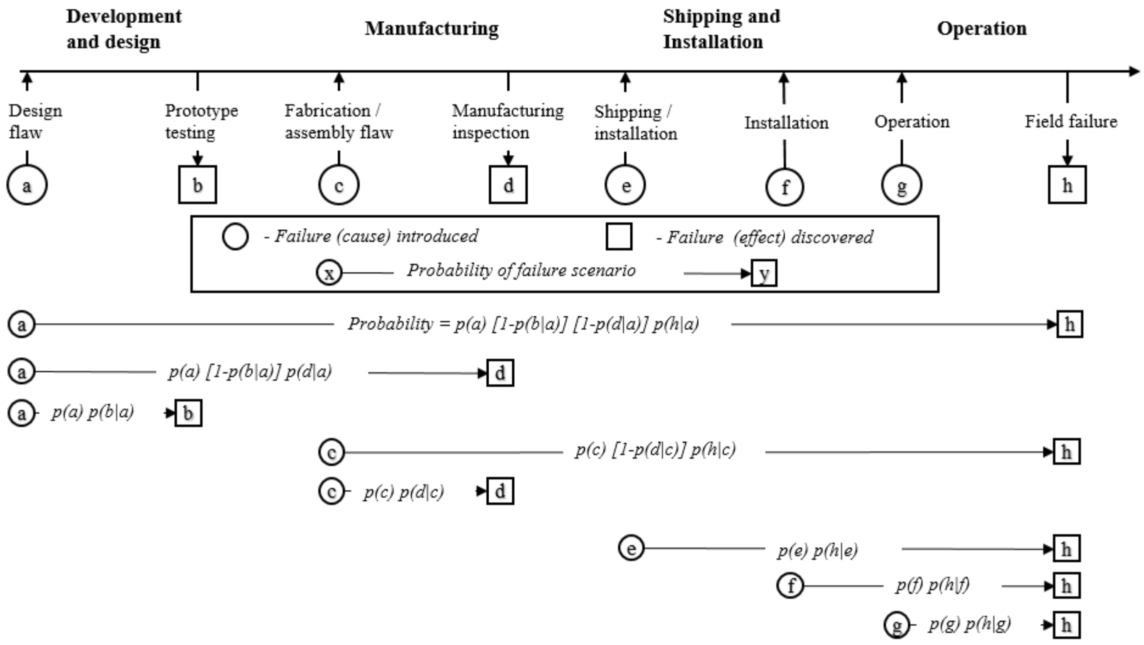


Figure 2-9. Product-life-cycle failure scenarios.

Note. Adapted from Kmenta (2001).

Kmenta states the probability of detection is part of the probability of failure and that a separate calculation is not needed. The failure cost is the probability of failure multiplied by the cost of failure occurrence, and the total failure cost is the summation of all failure scenarios for a given product. This results in the "total expected cost" shown in Equation 2-4.

Equation 2-4: Total expected cost (adapted from Kmenta (2001)

$$TEC = \sum_{i=1}^{n} p_i c_i$$

where p_i *is the probability failure i occurs,* c_i *is the cost associated with failure i, and n is the number of scenarios.*

Rhee and Ishii (2003) begin with the TEC calculation proposed by Kmenta (2001) and further define the cost of failure in a product while including a calculation for occurrence. This variable could be a one-time event or an expected number of occurrences over the life cycle of the product. Rhee and Ishii (2003) state the likelihood of detection and severity can be measured in terms of time loss. The cost of failure is shown to have three major categories: labor cost (LC), material cost (MC), and opportunity cost (OC).

Equation 2-5: Labor cost (adapted from Rhee and Ishii (2003)

$$Labor\ Cost = n\ x\ \{[DE * LR * PN] + [FT * LR * PN] + [DL * LR * PN]\}$$

where n is the number of occurrences, DE is the detection time, LR is the hourly labor rate, PN is the number of personnel, FT is the time to fix, and DL is the delay time.

Equation 2-6: Material cost (from Rhee and Ishii (2003)

$$Material\ Cost = n * CP$$

$where\ n\ is\ the\ number\ of\ occurrences,\ and\ CP\ is\ the\ cost\ of\ the\ product.$

Equation 2-7: Opportunity cost (from Rhee and Ishii (2003)

$$Oppurtunity\ Cost = [DE * FT * DL] * OC$$

$where\ DE\ is\ the\ detection\ time,\ FT\ is\ the\ time\ to\ fix,\ DL\ is\ the\ delay\ time,\ and$

$OC\ is\ the\ hourly\ opportunity\ cost.$

Rhee and Ishii (2003) introduce a modified FMEA table using the updated definition for failure cost, naming it life cost-based failure mode and effect analysis (LCB-FMEA). Going through the LCB-FMEA, the team establishes the labor cost, material cost, and opportunity cost, which can be summed for the total failure cost. The total failure cost is then multiplied by the probability of failure occurrence to give the total expected failure cost and is the prioritization metric in an LCB-FMEA analysis.

Table 2-15. LCB-FMEA

Failure Mode	Root cause of failure	Effect of Failure	Input										Output		
			Origin	Detection Phase	Recurring	Frequency	Detection Time (hr)	Fixing Time (hr)	Delay Time (hr)	Loss time	Quantity	Part Cost ($)	Labor Cost ($)	Material cost ($)	Opportunity Cost ($)

Note. Adapted from Rhee and Ishii (2003).

Rhee (2005) makes a further advancement on the life cost-based calculation. The labor cost and material cost calculations are modified using the given equations:

Equation 2-8: Labor cost (from Rhee (2005)

$$Labor\ Cost = r\ x\ \{[DE * LR * PN] + [FT * LR * PN * SN] + [DL * LR]\}$$

where r is the number of recurrences, DE is the detection time, LR is the hourly labor rate, PN is the number of personnel, SN is the number of systems affected by the failure, FT is the time to fix, and DL is the delay time.

Equation 2-9: Material cost (from Rhee (2005)

$$Material\ Cost = r * CP * SN$$

where r is the number of recurrences, CP is the cost of the product, and SN is the number of systems affected by the failure.

Rhee (2005) researches the reliability of a system—specifically, the ability of a system to perform its intended function at any given time. This is measured through the availability of the system, given by the following equation:

Equation 2-10: Availability (from Rhee (2005)

$$Availability = \frac{Uptime}{Scheduled\ operating\ hours} = \frac{MTBF}{MTBF + MTTR}$$

where MTBF is mean time between failure, and MTTR is mean time to repair.

Rhee (2005) performs a case study of the magnet system on a linear collider to predict the availability of the system at any given time. The linear collider has a target availability of 85%. Rhee uses a Monte Carlo simulation method (MCM) on the magnet subsystems, given their manufacturers reported MTBF and MTTR rates to account for uncertainty in the LCB-FMEA methodology. This simulation allows evaluation of different design alternatives to meet the system availability target. Rhee (2005) performed a comparison between traditional FMEA, LCB-FMEA, and LCB-FMEA with Monte Carlo simulation. As seen in Table 2-16, the failure cost varies for the different top failure modes with each method. Introducing the Monte Carlo simulation for probability estimation can significantly increase the failure cost of a failure mode due to uncertainty in the occurrence.

Table 2-16. Failure Cost vs. Method

Method	Failure Cost
RPN	$1.1M
LCB-FMEA	$5.2M
LCB-FMEA with MCM	$11.5M

Note. From Rhee (2005).

Rhee’s (2005) study shows how empirical data can be used to achieve desired reliability when designing a system.

Kmenta and Ishii (2005) perform an evaluation of RPN compared to cost-based prioritization metrics used during an FMEA. They use a SB-FMEA to compare to traditional FMEA. In traditional FMEA, there would be separate spreadsheets and evaluations of a component, subsystem, and system; this creates a disassociation between the separate spreadsheets because RPNs from different evaluations cannot be compared. The SB-FMEA allows for a component, subsystem, and system to be included in a comprehensive spreadsheet. In a previous study, Kmenta (2001) provides the total expected cost formula (Equation 2-4). Kmenta and Ishii (2005) use a theoretical example to estimate potential expected failure costs to RPN and include the following three assumptions in the calculation:

Assumption 1: “There is a consistent relationship between occurrence and probability” (Kmenta & Ishii, 2005, p.1031).

Assumption 2: “A consistent mapping exists between severity and cost” (Kmenta & Ishii, 2005, p.1031).

Assumption 3: “There is a scale relating detection to the probability of non-detection” (Kmenta & Ishii, 2005, p.1031).

Based on the industry, there can be a higher cost scale associated with severity such as in that of an aerospace organization compared to a flooring company. Kmenta and Ishii (2005) discover there can be different failure cost with the same RPN and different RPNs with the same failure cost. Therefore, RPN is not a predictor of expected failure cost. They also argues a change should only be implemented when it is cost effective, but there is no calculation presented to determine cost effectiveness.

The cost-oriented FMEA is introduced by von Ahsen (2008). von Ahsen states traditional FMEA is insufficient for ranking failure mode because there is no economic consideration to the failure mode. The lack of a cost factor makes it difficult to know where money for improvements should be spent. A failure mode found during a built-in-test would give a low likelihood of detection ranking and a low RPN even when there is a high cost associated with finding and repairing the failure mode. von Ahsen seeks to develop a modified FMEA risk prioritization metric with a cost base for prioritizing failure modes and allocating limited resources for corrective actions. von Ahsen proposes the cost-oriented RPN (RPN_C), which is focused on cost and probability of a failure reaching the customer. The RPN_C risk prioritization metric is a dollar value where higher dollar value indicates higher risk of failure mode. To compare the two methods, von Ahsen performs a cost-oriented FMEA and a traditional FMEA at an automotive supplier. During the process, the RPN_C formula is found too computationally difficult for the users at the automotive supplier, so the method is simplified to use probabilities expressed in terms of ranks, similar to traditional FMEA. The result shows that the cost-oriented risk prioritization metric, RPN_C, gives a different risk priority than the traditional RPN.

Table 2-17. Cost-Oriented FMEA vs. Traditional FMEA

Failure mode number	**Traditional RPN**	**Traditional ranking**	**RPN_C**	**New rank**
7	224	4	14953.48	1
9	112	7	4687.87	2
8	168	5	4351.60	3
12	112	7	1065.00	4

Note. From von Ahsen (2008).

2.2.6.2.2 Cost-Based FMEA Evaluation and Limitations

Gilchrist (1993) proposes a cost-based FMEA, replacing the RPN risk prioritization metric with failure cost. The cost metric is the product of the cost of failure, probability the failure reaches the customer, and probability the failure occurs. It is a measure that shows the cost incurred for a customer to receive a defective product. von Ahsen (2008) attempts to improve on Gilchrist's (1993) method by adding multiple probabilities of customer reactions and internal and external costs to the equation. The equation is so computationally difficult to perform that even FMEA experts do not use it during a case study (von Ahsen, 2008).

Kmenta (2001) states the probability of a defective product is part of the probability of failure and that a separate calculation in not needed. Kmenta (2001) introduces the total expected cost (Equation 2-4), which is a sum of various scenarios' individual failure costs that are the product of the probability of failure and failure cost. Rhee and Ishii (2003) and Rhee (2005) modify the failure-cost metric to include the life-cost factor by incorporating a product quantity to the metric and further defining the cost of failure through time loss. Kmenta and Ishii (2005) compare the RPN prioritization metric to the total failure-cost prioritization metric and conclude the RPN prioritization metric does not correspond to failure cost. Kmenta and Ishii (2005) also state an improvement or corrective action should be made on a product when the total cost to implement the action is the same or lower than the TEC. The TEC/EFC does address the ambiguity of the RPN prioritization metric formulation by removing the underlining fault with the multiplication of the SOD variables. The TEC/EFC is based on two ratio scales, probability and cost, where multiplication is an admissible process (Kmenta, 2001).

There are still limitations in the research with respect to the TEC/EFC replacing RPN as a prioritization metric. There is no equation or methodology present that defines the cost to implement an improvement or corrective action. The concept of limited resources is also not addressed in failure cost as a prioritization metric.

2.2.7 Research Gaps

Researchers identify multiple limitations to the FMEA process. The length of time to perform an FMEA and the life-cycle stage in which to perform FMEA are easily solved, but the ambiguity of the RPN prioritization metric is a true flaw. There have been attempts to modify the RPN by adding weight factors or variables and changing the RPN formula, but the modifications use multiplication of ordinal variables, which is an improper mathematical transformation (J. Bowles, 2004; Kmenta, 2001; Rhee & Ishii, 2003).

The largest concentration of studies devoted to addressing the ambiguity of the RPN prioritization metric are in fuzzy-based analysis, grey relational theory, and cost-based metrics (H.-C. Liu et al., 2013). Fuzzy-based analysis and grey relational theory have shown that common RPN values can mask enhanced risk for a particular failure mode and can reduce the number of common prioritization values (Aikhuele & Turan, 2016; L.-Y. Chen & Yeh, 2014; Pillay & Wang, 2003). The prioritization metrics produced by fuzzy theory (i.e., FRPN) and grey theory (i.e., grey relational coefficient) cannot be compared to other studies and are on an interval scale. The interval scale shows a possible range of values, but position between values are not relative to one another (Terrell, 2016). An FRPN of 500 is twice that of an FRPN of 250, but this does not mean that the failure mode is at twice the risk. H.-C. Liu et al. (2013) show that the time and expense involved with creating membership functions and complex calculations can lead to information loss and detract from the methods use in practice. Fuzzy-based analysis and grey theory, which use SOD variable rankings, multiple linguistic terms, and membership functions, do not address the underlying SOD variable weakness of the RPN metric. Multiplying the subjective SOD variables is the first incorrect step. Any transformation or weighting after multiplying is masking the fundamental weakness of the RPN prioritization metric. Fuzzy-based analysis and grey theory only reduce the chance of having a similar RPN value, thus making the ranking seem more effective.

Cost-based FMEA replaces the SOD variables with the ratio values for cost and probability, thus removing the underlying weakness of the ordinal SOD variables. von Ahsen (2008) demonstrates that a failure-cost prioritization metric that is computationally complex is not likely to be accepted in practice. The proposed methods do not define an economic factor for corrective action or resource allocation. The methods use expected failure cost as the prioritization metric but do not include a provision to evaluate effectiveness.

More work is needed to determine the best way to measure and prioritize risk. A new risk prioritization method must have a decision-support system to determine when to implement a corrective action or improvement (H.-C. Liu et al., 2016). This is necessary because not all corrective actions or improvements can be deployed on a system due to finite resources, including schedule and budget (Khorshidi, Gunawan, & Ibrahim, 2016). Corrective actions or improvements should also not be implemented if they are not economically sustainable (Carmignani, 2009; Cheah et al., 2011; Kmenta & Ishii, 2005).

CHAPTER III

ECONOMIC IMPACT FMEA METHODOLOGY

This chapter introduces the economic impact failure mode and effects analysis (EI-FMEA) methodology. I first explain the concept and objectives of the methodology. Next, I present the input variables for the probability of failure and the cost of failure. The failure cost calculation is discussed along with a detailed explanation of the economic-impact-value (EIV) risk prioritization metric. This chapter concludes with the EI-FMEA spreadsheet template and a research summary.

3.1 Economic Impact FMEA

FMEA is a dependability analysis technique in use since the 1940s. It is a tool meant to improve the quality of a product, system, software, or process through the reduction of potential failures by implementing corrective actions, but inherent limitations, like the RPN metric, make traditional FMEA ineffective (Jiang et al., 2016). Many attempts have been made to improve the FMEA method and the RPN metric, with varying success (H.-C. Liu et al., 2013). Cost-based methods (Kmenta & Ishii, 2005; Rhee, 2005) replace the RPN with an expected-failure-cost metric that addresses some of the limitations found in the body of knowledge, but more work is needed to refine the approach.

The EI-FMEA is a cost-based method that replaces the RPN metric with the EIV risk prioritization metric which measures risk in terms of economic loss due to a failure event by looking at what can go wrong, the probability of occurrence, and the effect of occurrence. The EIV risk prioritization metric is a decision-support system that ranks corrective actions based on failure-cost reduction and determines when a corrective action should be implemented.

3.2 Probability of Failure

Probability theory measures the randomness and uncertainty that governs events. In probability theory, probability is the chance of an event or given outcome. Prior to the event, it is impossible to say which outcome will occur (Borovkov, 2013). For failure analysis, probability is the chance of a failure event occurring over a period of time. Take the example of a manufacturing process that fabricates pressure valves. A random sample size of 100 (i.e., n=100) is chosen from a population of parts to test the pressure valve, and the number of failures (i.e., not meeting the specified pressure requirement) in the sample is recorded.

Table 3-1. Pressure Valve Failure

Sample set	**Number of failures**
1	6

Equation 3-1. Probability of failure

$$Probability\ of\ failure = \ p_f = \frac{Fn}{n}$$

$where\ Fn\ is\ the\ number\ of\ failures\ and\ n\ is\ the\ sample\ size.$

In the first sample set, the probability of a pressure valve not meeting its pressure specification is 6/100 = .06 or 6%. While the probability of failure for the sample set is 6%, this may not be representative of the entire population. The experiment is extended to include 100 sample sets with 100 components in each set.

Table 3-2. Pressure Valve Failure

	Sample set	**Number of failures**
	1	6
	2	3
	….	
	99	5
	100	2
Total	10000	364

Using 100 samples sets with 100 components in each set, there are 364 failures. The probability of a pressure valve not meeting its pressure specification is 364/10000 = .0364 or 3.64%. As the number of trials or sample sets increases, the probability of failure approaches a constant rate (Taylor, 2012). For the pressure valve example, an estimation of the probability of failure would be 3.64%.

In section 2.2.5.3.1, I introduce the ambiguity of the probability of occurrence variable for FMEA. Traditional FMEA converts the probability of failure into an ordinal value that is often between 1 and 10. This can lead to an ambiguous scale where the probability of failure can vary widely, depending on the industry (see Figure 3-1).

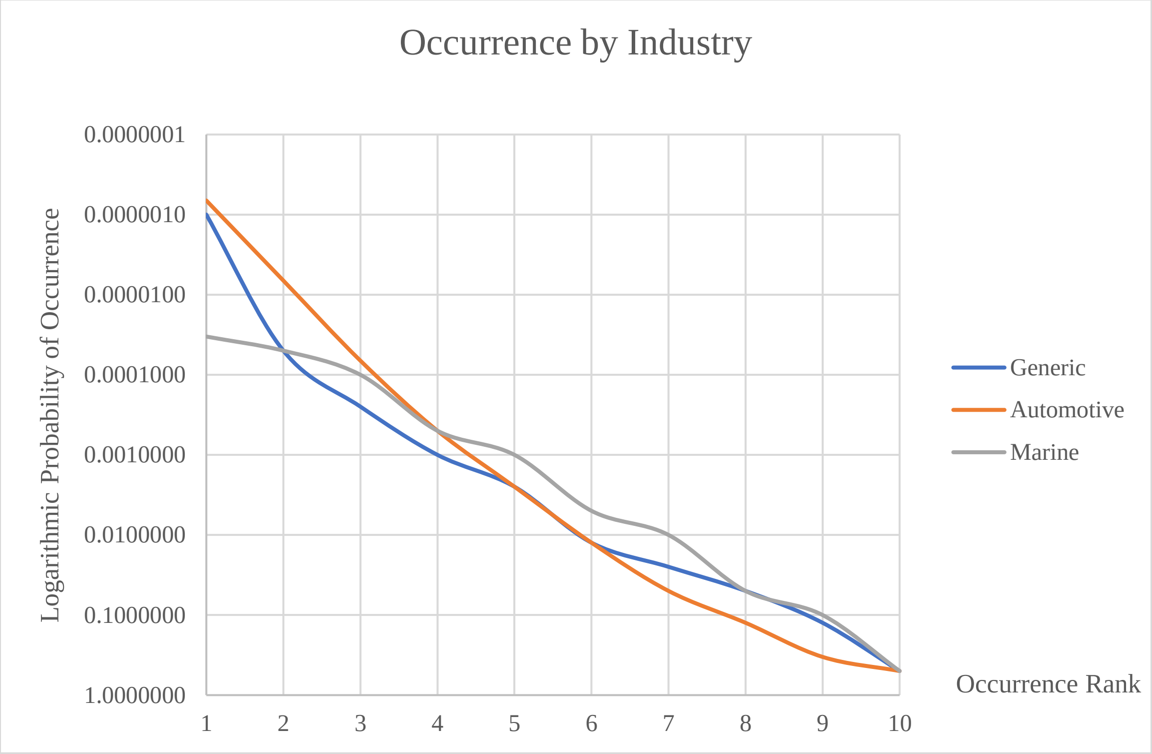


Figure 3-1. Occurrence by industry scale.

Removing the ordinal scale addresses the ambiguity of the probability of occurrence variable by replacing it with the probability of failure.

3.2.1 Failure Scenarios

In traditional FMEA, individual FMEAs are applied at each system level where failure modes are listed by cause and effect. This relationship, shown as a cause-and-effect chain, can lead to confusion when the effect of the failure is not observed until a higher system level. Figure 3-2 shows a block diagram for a system that has four levels, where a failure cause at *Subassembly e* may become a failure effect at *Assembly C*. Traditional FMEA uses separate spreadsheets for each system level, which can obscure the true cause-and-effect chain throughout an entire system (Kmenta & Ishii, 2005).

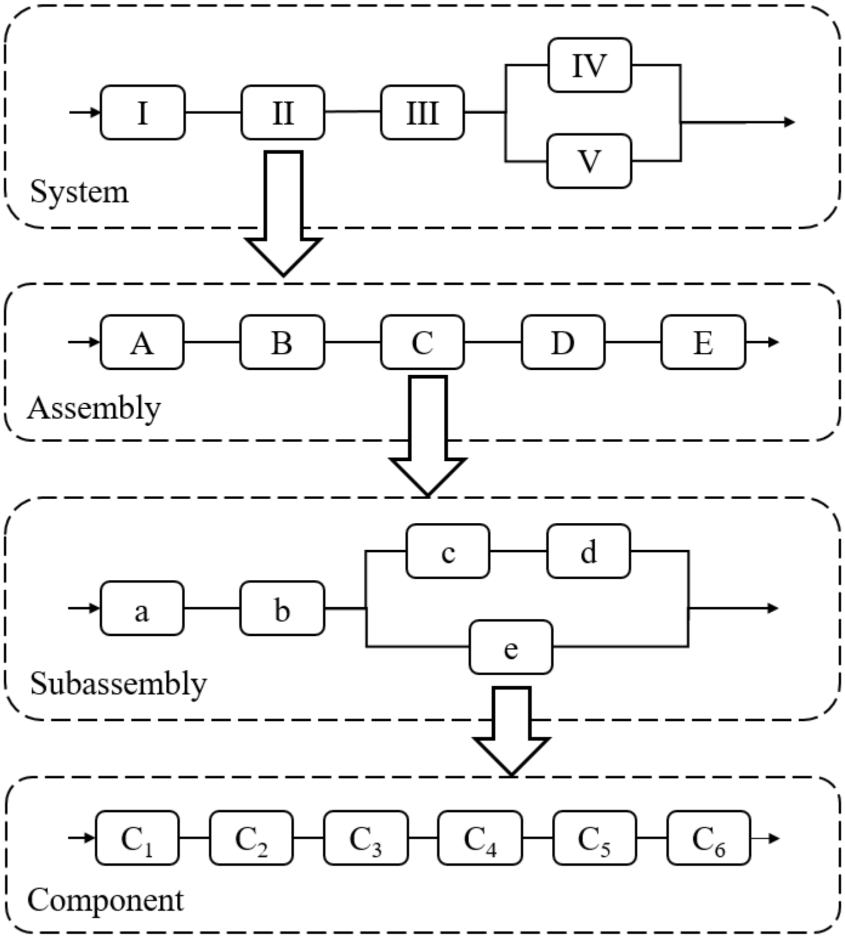


Figure 3-2. Block diagram of system to component level.

Note. Adapted from Birolini (2014).

Kmenta and Ishii (2005) introduce the concept of *failure scenarios*. In failure scenarios, the entire system is placed on a single spreadsheet to show the full extent of the cause-and-effect chain. A failure scenario is defined as an undesired cause-and-effect chain where there is a probability of negative consequence for each potential failure scenario (Kmenta & Ishii, 2005). Using failure scenarios, users can look at potential failure chains throughout a product's life cycle. For example, a failure effect on *System II* can be shown from a failure cause at *Component* C_1.

3.2.1.1 Marine Engine Water Pump

In marine craft engines, a cooling system circulates fluid through the engine block. The cooling system includes the following components: a water pump impeller, a water pump housing, a water pump top plate, and a thermostat. The impeller is made from a flexible material that conforms to the water pump housing to create a low- and high-pressure side during rotation to circulate fluid through the engine. The top plate on the water pump housing has a gap setting to allow the impeller to rotate freely while providing sufficient pressure and flow rates. A gap setting that is too small can cause binding in the impeller, reducing the flow rate, while a setting that is too large can cause a loss of pressure which also reduces the flow rate. Figure 3-3 shows a failure scenario map for the water pump. There are 16 failure scenarios possible across the life cycle of the cooling system, where each of the scenarios becomes a row on the FMEA spreadsheet. In the failure map, a failure mode introduced during fabrication could cause an effect at manufacturing inspection or during the operation period.

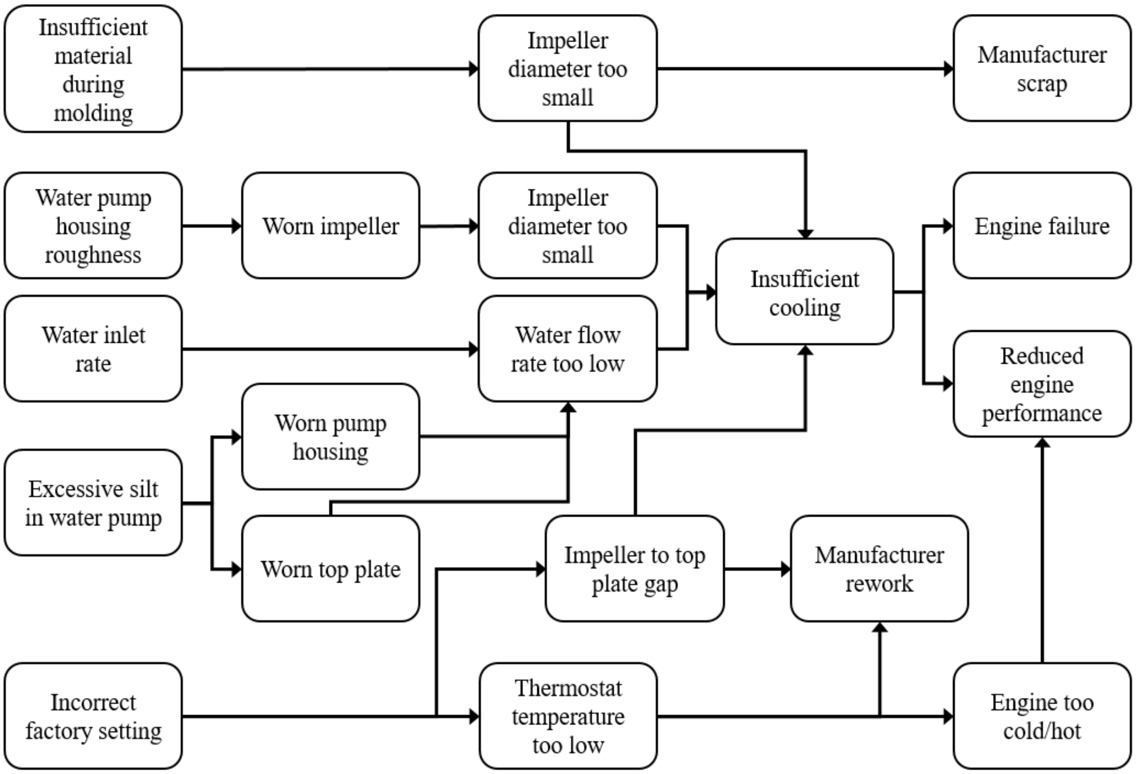


Figure 3-3. Failure scenario map for marine craft engine cooling system.

3.2.2 Life Cycle Failure Probability

In life cycle failure probability, there are failures introduced (i.e., cause) and failures discovered (i.e., effects). The chain connecting the failure cause to the failure effect is the failure scenario. Throughout the life cycle, cause and effects may be introduced at multiple locations. Design, manufacture, installation, and operation are the four main categories in a product’s life cycle (Rhee, 2005). At each of the categories, there is a chance for a failure to be introduced as well as a chance for a failure to be discovered. Figure 3-4 shows the different points where failures can be introduced or discovered based on their location in the product’s life cycle. The probability of the failure scenario is the product of the probability of introduced failure by the probability of discovered failure in a given life cycle. Probability of the failure scenario can also be understood as the product of the probability of the cause and the probability of the effect.

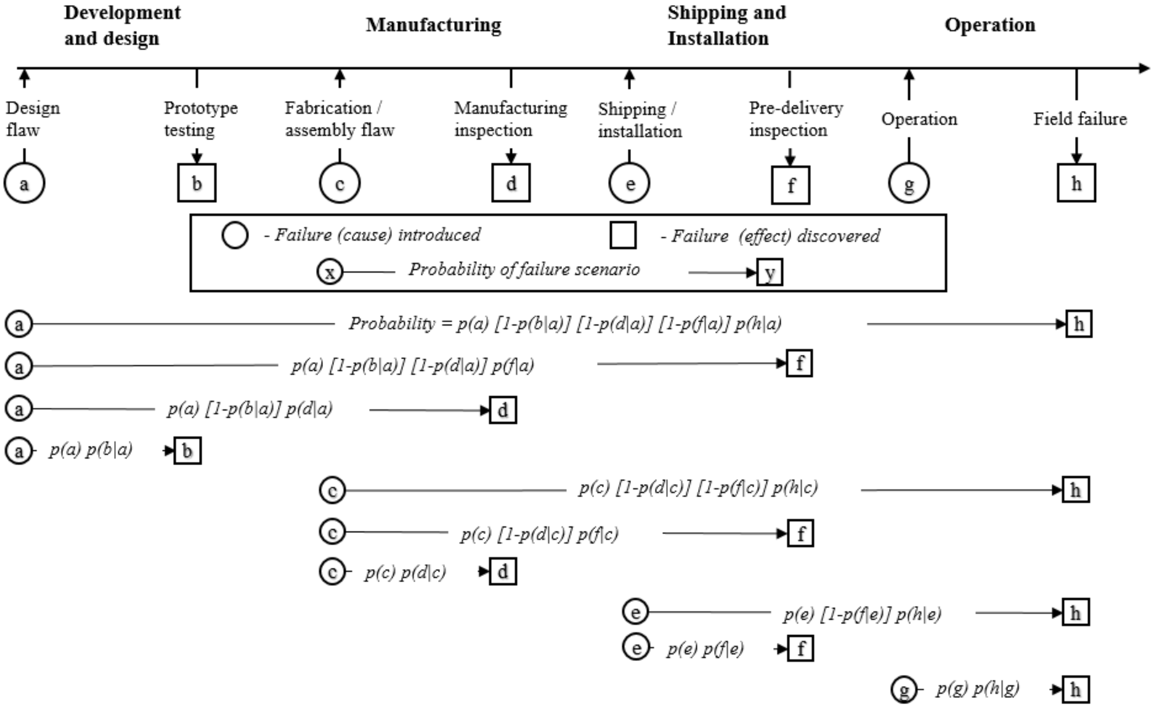


Figure 3-4. Probability of failure by life cycle.

Note. Adapted from Kmenta (2001).

The marine engine water pump introduced in section 3.2.1.1 has 16 potential failure scenarios. The first failure cause is *insufficient material during molding*. This cause has three potential failure effects: *manufacturer scrap*, *engine failure*, and *reduced engine performance*. The failure is introduced during the manufacturing life cycle during fabrication ((c) in Figure 3-4). The failure effect can be identified at the manufacturing inspection step (d) or during the operation life cycle as a field failure (h). The first potential failure scenario is *insufficient material during molding* (i.e., *p(c)*), leading to *manufacturer scrap* (i.e., *p(d|c)*). Using the probability block diagram in Figure 3-5, the probability of the failure scenario is defined by;

$$Probability\ of\ failure\ scenario\ 1 = p(1) = p(c) * p(d|c) = .01 * .9 = 0.009 = 0.9\%.$$

The same process is used to define failure scenario 2 (i.e., *engine failure*) and failure scenario 3 (i.e., *reduced engine performance*):

$$p(2) = p(c) * [1 - p(d|c)] * [1 - p(f|c)] * p(h|c) = .01 * .1 * 1 * (.1 * .2) = 0.00002;$$

$$p(3) = p(c) * [1 - p(d|c)] * [1 - p(f|c)] * p(h|c) = .01 * .1 * 1 * (.1 * .8) = 0.00008.$$

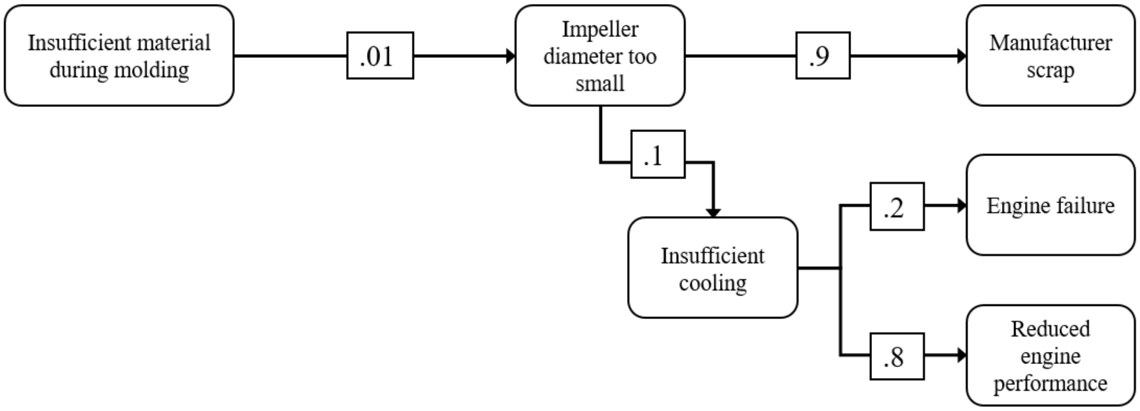


Figure 3-5. Failure probability block chart.

For failure scenarios 2 and 3, *pre-delivery inspection* cannot discover the failure; therefore, the probability is zero. There are two possible failures that could be discovered as a *field failure*, where the sum of the probabilities of failure are equal to 1.

3.3 Failure Cost

A common way to measure risk is to determine the monetary impact of an event occurrence. When that event is failure, failure cost is the monetary measure of the risk. The cost of quality gives the concept of failure cost—the cost associated with finding and fixing products that do not meet their intended purpose or specification (Juran & Godfrey, 1999). Failure cost combines both internal and external failure costs and is a universal way to measure the severity or impact of a failure. There are challenges associated with determining failure cost; cost can raise exponentially the further away a failure cause and failure effect occur from each other in the life cycle. Failure cost includes repair times, component costs, lost opportunity costs, and external failure costs.

3.3.1 Repair Time and Cost Determination

The total time required to determine the root cause of a failure and return a product to the previous known good condition is called the repair (restoration) time (Birolini, 2014). There are multiple variables for the repair time. After a failure effect is discovered, the time associated with determining the root cause is the detection time. The renewal time is the time it takes to fix, repair, or rework a failure to return to a known good condition. This includes the total hours for all personnel to remanufacture, reinstall, repair, or rework a product, as well as any delay or downtime during the process.

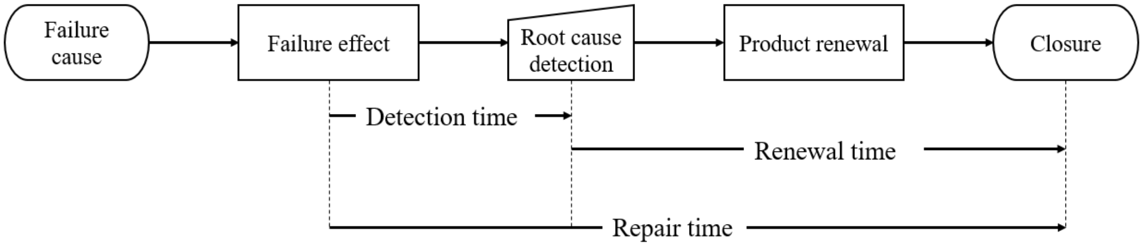


Figure 3-6. Repair time flow chart.

Repair time factors into the equation for repair cost (Equation 3-2). To determine repair cost, the repair time can use any time of measure, but the unit needs to be consistent throughout the equation. The time durations are the total labor time (e.g., hours) for the personnel addressing the failure, and the labor rate is the value per unit of time (e.g., dollars per hour) of the personnel.

Equation 3-2. Repair cost.

$$Repair\ Cost(CR) = (DT + RT) * LR$$

$where\ DT\ is\ the\ total\ detection\ time, RT\ is\ the\ total\ renewal\ time, and\ LR\ is\ labor\ rate\ per\ unit\ of\ time\ for\ the\ personnel\ involved.$

The equation can be expanded if there are multiple labor rates for the personnel involved. When that occurs, the individual repair cost per labor rate (e.g., personnel discipline) is calculated and summed. For example, Table 3-3 shows a failure that requires both engineers and technicians to detect and renew the product. The repair cost per personnel is calculated and summed for the total repair cost.

Table 3-3. Repair Cost by Personnel

Personnel	**Detection time (hr)**	**Renewal time (hr)**	**Labor rate ($/hr)**	**Repair cost**
Engineer	4	2	$ 150.00	$ 900.00
Technician	1	12	$ 75.00	$ 975.00
			Total	**$ 1,875.00**

3.3.2 Component Cost Determination

When a failure occurs, an evaluation is performed to determine the root cause. After identifying the root cause, the renewal phase is initiated. To return a product back to specification, there often are costs associated with replacing or repairing components. Component costs are the actual monetary value used in the renewal of a product. For example, a circuit board that no longer supplies power per the original specification reveals a burst capacitor on the circuit board during the failure investigation. Replacing the capacitor returns the circuit board back to the original specification. The component cost to renew the circuit board is the cost of the new capacitor.

Equation 3-3. Component cost.

$$Component\ cost\ (CC) = \sum_{i=1}^{n} c_i$$

$where\ c_i\ is\ the\ cost\ of\ component\ i\ and\ n\ is\ the\ number\ of\ components.$

3.3.3 Lost Opportunity Cost Determination

Another component to failure cost is the lost opportunity cost which is the missed value due to a failure. Lost opportunity cost is often calculated for a system or piece of equipment that produces value to a product. For example, a computer-controlled mill machines water passages into a cooling plate. The cooling passages increase the value of the water plate by $50. In an 8-hour shift, 20 cooling plates are machined on the mill. The opportunity cost (e.g., dollars per hour) of the mill can be found using Equation 3-4.

Equation 3-4. Opportunity rate.

$$Opportunity\ rate\ (OC) = VA/t$$

$where\ VA\ is\ the\ monetary\ value\ added\ over\ time\ interval\ t.$

The lost opportunity cost is then calculated by taking the product of the repair time and opportunity rate (Equation 3-5).

Equation 3-5. Lost opportunity cost.

$$Lost\ opportunity\ cost(LC) = (DT + RT) * OC$$

where DT is the total detection time, RT is the total renewal time, and OC is the opportunity rate.

3.3.4 External Failure Cost Determination

External failure cost occurs when an item is found to be non-conforming to its specification after it leaves the manufacturing plant and the customer has received it. It is a collection of costs that occur when a failure affects the end-user. While some of the costs are visible, others are non-visible and can be difficult to determine as we discussed in section 2.1.2. Equation 3-6 provides a summation of the visible external failure costs.

Equation 3-6. External failure cost.

$$External\ failure\ cost\ (EC) = WC + RC + IC + DC + FC + LS$$

where WC is the warranty cost, RC is the cost of product recalls, IC is the cost of complaint investigation, DC is the cost of discounts made to a customer, FC is the cost of penalty fees, and LS is the cost of lawsuits.

3.3.5 Failure Cost Determination

The total failure cost is the sum of the repair cost, component cost, lost opportunity cost, and external failure cost (Equation 3-7). It represents the monetary cost per failure event that occurs over a product's life cycle if no corrective actions are taken.

Equation 3-7. Failure cost.

$$Failure\ cost\ (C) = CR + CC + LC + EC$$

where CR *is the repair cost,* CC *is the component cost,* LC *is the lost opportunity cost, and* EC *is the external failure cost.*

3.4 Expected Failure Cost

The expected failure cost (EFC) is a concept first introduced by Gilchrist (1993) and later modified by Kmenta and Ishii (2005) and Rhee (2005). EFC measures the potential risk or loss from a failure event. In its basic form, the EFC is the product of the number of products affected, probability of failure, and cost of failure. Equation 3-8 represents the total expected failure cost of the sum of all potential failure scenarios for a given failure mode.

Equation 3-8. Expected failure cost.

$$Expected\ failure\ cost = \sum_{i=1}^{n} C_i * p_i * q_i$$

where p_i *is the probability of failure* i*,* C_i *is the cost associated with failure* i*,* q *is the total quantity affected by failure* i *and* n *is the number of failure scenarios.*

3.4.1 Expected Failure Cost of Automotive Fuel System

An automotive fuel system has a specification to supply gasoline to an engine at a flow rate of 400 to 420 pounds per hour (lb/hr) and a pressure of 60 psi. A potential failure mode for the fuel system is an inadequate fuel flow rate (e.g., less than 400 lb/hr). Table 3-4 shows the total EFC for an inadequate fuel flow rate for the automotive fuel system. There are three failure causes that result in four distinct failure effects. The quantity is the number of fuel systems that are produced in a year. The four failure scenarios result in an EFC of $601,460 per year.

Table 3-4. Fuel System EFC

Failure Mode	Root Cause	Failure Effect	Quantity (per year)	Probability of Failure	Failure Cost	EFC
Inadequate fuel flow	Fuel line exceeds minimum bend radius	Engine power loss	34000	0.006	$450	$91,800
	Fuel line deterioration	Engine stalls under load	34000	0.0002	$450	$3,060
	Fuel pump voltage is low	Engine stalls	34000	0.02	$120	$81,600
	Fuel pump is clogged	Engine does not start	34000	0.05	$250	$425,000
					Total EFC	$601,460

Note. The quantity is the number of fuel systems produced in a year

3.4.2 Expected Failure Cost Importance

In traditional FMEA, the SOD variables are used to measure the risk of a failure mode. In section 2.2.5.3.1, multiple instances of ambiguity with respect to the SOD variables are presented. For EI-FMEA, the SOD variables are replaced by the EFC to measure the baseline risk of a failure mode. The EFC converts the risk to a monetary value and permits the failure mode to be compared to other failure modes within the same analysis and to other analyses performed on different products. Evaluating risk based on monetary value allows for a universal translation.

3.5 Corrective Actions

In failure analysis, finding the root cause of the failure is only part of the objective. The next objective is to investigate potential corrective actions. This is known as root cause corrective action. The EFC is the monetary value over the given time frame when no steps are taken to reduce the failure mode. A corrective action thus reduces the probability or cost of the failure mode, thereby reducing the potential failure cost. A new probability of failure and new failure cost are determined based on the corrective action. After the root cause of a failure is determined, the company looks to replace (renew) the product affected by the failure, as well as for ways to reduce the chance for reoccurrence.

One of the pros of traditional FMEA is the recalculation of the RPN number due to a corrective action. Recalculation allows the user to determine, based on a reduction of the RPN, if a corrective action should be implemented. In current cost-based FMEA methods, there is no provision for the evaluation of a corrective action. The risk rank is based solely on the EFC. By only relying on the EFC, the cost to implement a corrective action is not considered.

3.5.1 Implementation Cost

The implementation cost is the one-time cost required to implement a given corrective action. This can include the costs to redesign a product, requalify a product, create new drawings, update processes, purchase new manufacturing equipment, or find new component suppliers. There is also a recurring implementation cost in EI-FMEA that occurs when the base cost of the product changes as a result of the corrective action or new components are introduced or replaced from the initial design. The recurring implementation cost (Equation 3-9) is found by summing the initial or baseline components of a product affected by a particular failure mode and subtracting the summation of the components of the product after implementation of a corrective action. If none of the components has changed or no new processes introduced, the value is zero.

Equation 3-9. Recurring implementation cost.

$$Recurring\ implemention\ cost\ (\Delta CC) = \sum_{i=1}^{n} CC_i - \sum_{j=1}^{m} CC_j$$

$where\ CC_i\ is\ the\ initial\ cost\ of\ components\ i, n\ is\ the\ number\ of\ components, CC_j\ is\ the\ new\ cost\ of\ components\ j\ (i.e., the\ components\ used\ after\ the\ corrective\ action\ implemenation), and\ m\ is\ the\ number\ of\ components\ after\ corrective\ action\ implemenation.$

3.5.2 Adjusted Expected Failure Cost

The adjusted failure cost (AFC) is the delta EFC with the inclusion of the corrective action. The corrective action is intended to reduce the EFC and can be undertaken by reducing the probability of failure, the failure cost, the recurring implementation cost, or the combination of any of the three. The AFC determines the monetary impact of the corrective action on the failure mode.

3.5.2.1 Calculating the Adjusted Failure Cost

The EFC equation, Equation 3-8, is modified to become the AFC equation. The failure cost and probability of failure are replaced by the new failure cost and probability of failure after the implementation of the corrective action. The recurring implementation cost and implementation cost are new variables added for the AFC equation. Equation 3-10 represents the total adjusted failure cost of the sum of all potential failure scenarios for a given failure mode after a corrective action has been implemented.

Equation 3-10. Adjusted failure cost.

$$AFC = \sum_{k=1}^{n} (C_k * p_k * q_k * \Delta CC_k) + IC_k$$

where C_k *is the failure cost after CA k,* p_k *is the probability of occurrence after CA k,* q *is the total quantity affected after CA k,* ΔCC_k *is the reoccurring implementation cost of CA k, and* IC_k *is the implementation cost of CA k, and* n *is the number of failure scenarios.*

Using the fuel system example from section 3.4.1, the implementation of the corrective action is evaluated in Table 3-5 using the AFC.

Table 3-5. Fuel System AFC

Item Number	Failure Mode	Root Cause	Failure Effect	Quantity (year)	Probability of Failure (p_i)	Failure Cost (C_i)	EFC	Corrective Action	Implementation Cost	Recurring Implementation Cost	Probability of Failure (p_k)	Failure Cost (C_k)	AFC
1	Inadequate fuel flow	Fuel line exceeds minimum bend radius	Engine power loss	34000	0.006	$450	$91,800	New fuel line routing	$3,000	$0	.0005	$450	$10,650
2		Fuel line deterioration	Engine stalls under load	34000	0.0002	$450	$3,060	Replace rubber hose with Teflon-lined hose	$3,000	$10	.0001	$450	$18,300
3		Fuel pump voltage is low	Engine stalls	34000	0.02	$120	$81,600	Protect fuel pump power wire from corrosion with environmental cap	$2,000	$0.50	.01	$120	$22,400
4		Fuel pump is clogged	Engine does not start	34000	0.05	$250	$425,000	Add pre filter to fuel pump intake.	$5,000	$5	.01	$200	$345,000

In Table 3-5, the AFC decreases for items 1, 3, and 4 while increasing for item 2. The AFC method also allows for comparison and selection of the corrective action. Like EFC, minimization of the AFC is the goal.

Table 3-6 shows a comparison of three different corrective actions the engineering staff could use to address the root cause of the fuel line exceeding the minimum bend radius. “Optimize fuel line routing” provides the minimum AFC and thus is the best potential corrective action.

Table 3-6. AFC Corrective Action Comparison

Item Number	**Root Cause**	**Failure Effect**	**Corrective Action**	**Implementation Cost**	**Recurring Implementation Cost**	**Probability of Failure (p_k)**	**Failure Cost (C_k)**	**AFC**
1	Fuel line exceeds minimum bend radius	Engine power loss	Optimize fuel line routing	\$3,000	\$0	.0005	\$450	\$10,650
			Replace hose bends with hard line fittings	\$5,000	\$50	.0001	\$650	\$113,500
			Replace rubber hose with hard line	\$3,000	\$150	.0001	\$800	\$463,500

3.6 Economic Impact Value

The EIV is the risk prioritization metric for the EI-FMEA method. It is a comparison between the EFC and the AFC that also determines if a corrective action should be implemented. The EIV is found by subtracting the AFC from the EFC (Equation 3-11). A smaller number indicates larger savings (i.e., reduced failure cost) through the implementation of a corrective action, and a positive number indicates the corrective action should not be implemented because it is not cost effective. Risks are then ranked according to EIV numbers. EIV below zero are ranked in ascending order with the smallest number starting at 1 and values that are zero and above are marked as “no change or NC.” Implementing a corrective action on a value below zero indicates savings, a value of zero indicates no economic benefit, and a value higher than zero indicates additional cost.

Equation 3-11. Economic impact value.

$$EIV = AFC - EFC$$

The corrected failure cost (CFC) is the inherent failure cost associated with a given failure mode. It is determined by taking the minimum of the EFC and AFC.

Equation 3-12. Corrected failure cost.

$$CFC = \min(EFC, AFC)$$

3.6.1 Calculating Economic Impact Value

The EIV calculations for the fuel system example are shown in Table 3-7.

.

Table 3-7. Fuel System Economic Impact Value

Item Number	Failure Mode	Root Cause	EFC	Corrective Action	AFC	EIV	Risk Rank	CFC
1	Inadequate fuel flow	Fuel line exceeds minimum bend radius	$91,800	Optimize fuel line routing	$10,650	$-81,150	1	$10,650
2		Fuel line deterioration	$3,060	Replace rubber hose with Teflon-lined hose	$18,300	$15,240	NC	$3,060
3		Fuel pump voltage is low	$81,600	Protect fuel pump power wire from corrosion with environmental cap	$22,400	$-59,200	3	$22,400
4		Fuel pump is clogged	$425,000	Add pre filter to fuel pump intake.	$345,000	$-80,000	2	$345,000

3.6.2 Interpreting Economic Impact Value

The EIV is the potential savings from the implementation of a corrective action. EIV can also determine if a corrective action is cost effective. In Table 3-7, there is a negative EIV for items 1, 3, and 4. The risk prioritization rank gives the highest ranking to item 1. This shows the most possible savings come from addressing the failure mode in item 1. Item 2 has an EIV value of $15,240, showing that implementation of the corrective action costs more money than it will save. The risk prioritization rank is NC, meaning no corrective actions are pursued. Using the EIV's risk prioritization rank allows more focus on failure cost reduction.

3.7 EI-FMEA Procedure

The EI-FMEA procedure is similar to the traditional FMEA procedure. A cross-disciplinary team is assembled to evaluate current products. Using the EI-FMEA method, different levels of product structure (e.g., components and systems), processing items, and design items can be combined in a single study, but design and process studies are often performed separately to save time. EI-FMEA normally uses a bottom-up approach to look at individual components and how failures at the component level can affect later systems and subsystems. At times, a team may use a top-down approach early in the life cycle, when individual components are not fully defined. The EI-FMEA flowchart is shown in Figure 3-7.

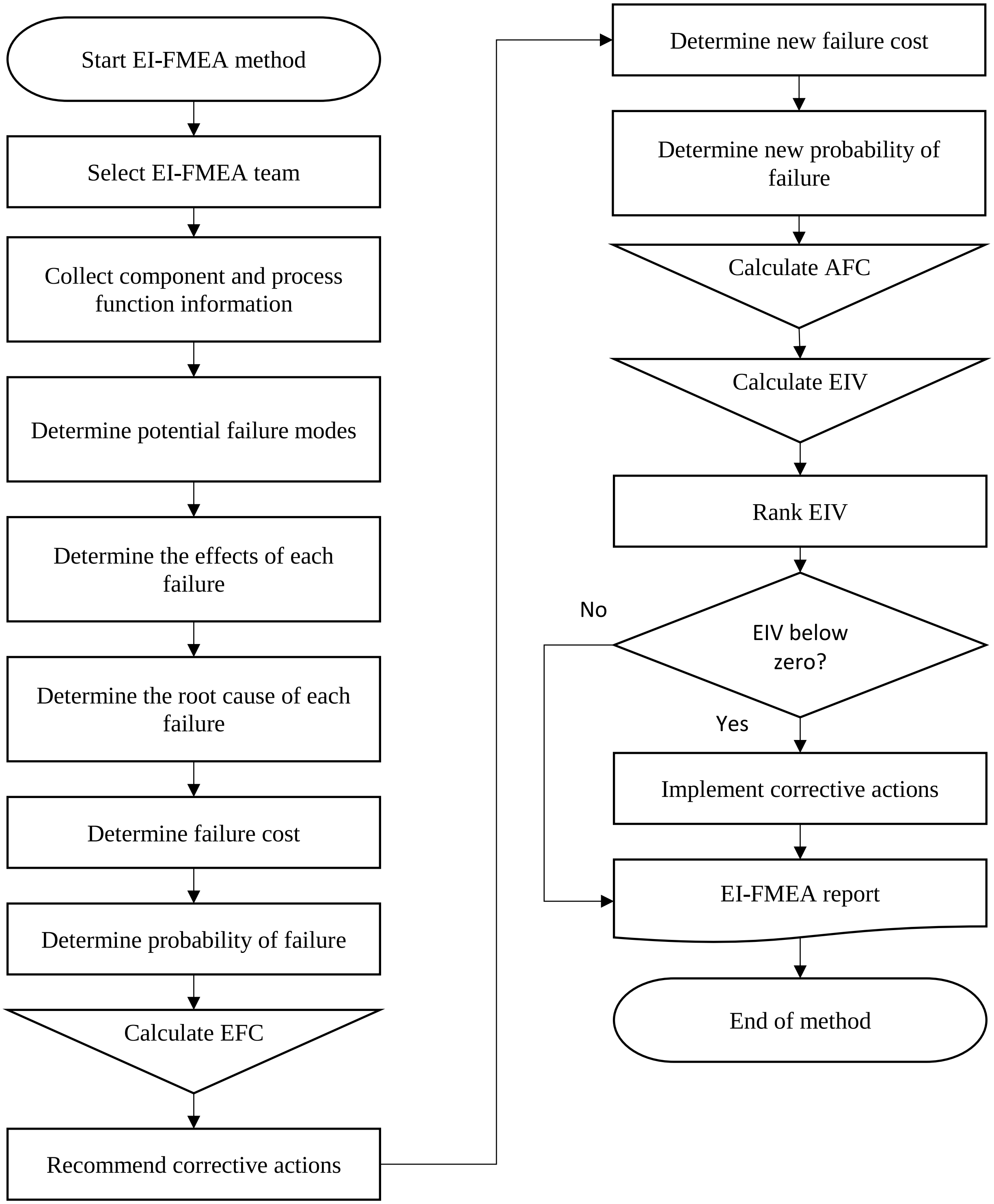


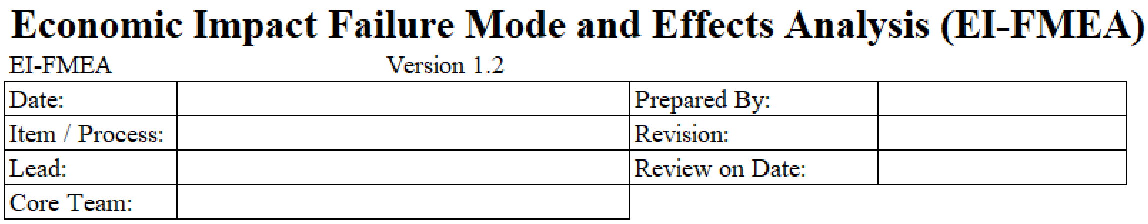
Figure 3-7. EI-FMEA flowchart.

The established EI-FMEA team begins by collecting component and process function information. This can include performing preliminary risk assessments, creating functional block diagrams, or constructing function state models. Potential failure modes are then listed along with all potential scenarios for failure effects and their root causes. The next step is to calculate the failure cost and probability of failure for each root cause and failure effect.

After finding the probability of failure and failure cost, the EFC is calculated. The team then determines a corrective action for the root cause and calculates a new probability of failure and failure cost if the corrective action is implemented. The AFC is found using these new values. Comparing the EFC and AFC reveals the EIV that results from the implementation of the corrective action. The EIV is the risk prioritization metric where values below zero receive an ascending numeric value to rank failures based on the largest cost savings of the corrective action. Values that are zero or greater indicate that the corrective action is not cost effective, and these values do not receive a risk rank value. The EI-FMEA team's final step is to document the results in a report that is re-evaluated on a time interval chosen by the team.

3.7.1 EI-FMEA Template

EI-FMEA is spreadsheet based to organize and calculate the team's inputs. The beginning of the spreadsheet has a title block (Figure 3-8) that includes the date, item or process being evaluated, team members, revision, and review periods.



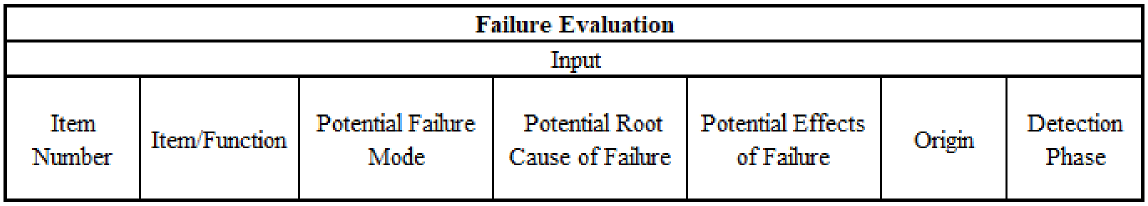
Economic Impact Failure Mode and Effects Analysis (EI-FMEA)

EI-FMEA Version 1.2

Date:		Prepared By:	
Item / Process:		Revision:	
Lead:		Review on Date:	
Core Team:			

Figure 3-8. EI-FMEA template title block.

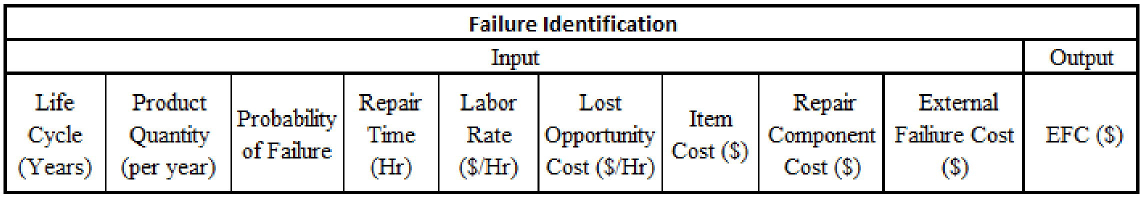
The body of the spreadsheet has four main groups: failure evaluation, failure identification, corrective action, and prioritization. The failure evaluation group (Figure 3-9) includes the item number, item function, potential failure modes, potential root cause, potential effects of failure, and life-cycle categories for the origin and detection phase.



Failure Evaluation						
Input						
Item Number	Item/Function	Potential Failure Mode	Potential Root Cause of Failure	Potential Effects of Failure	Origin	Detection Phase

Figure 3-9. EI-FMEA template, failure evaluation.

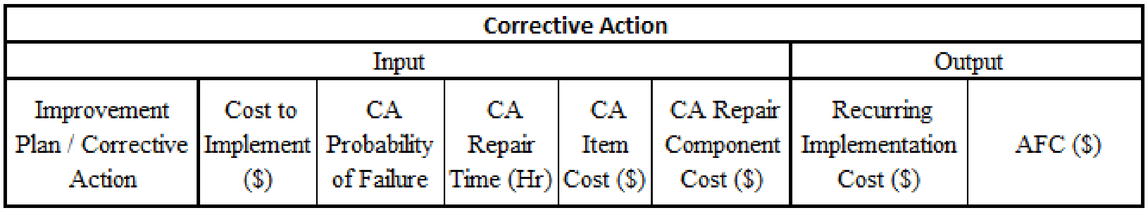
The next section is the failure identification group (Figure 3-10). For this part of the spreadsheet, the inputs used to determine the EFC are added. The section begins with the product life cycle in years and the product quantity per year. Next is the probability of failure, followed by the repair time in hours, the labor rate in dollars per hour, and the lost opportunity cost in dollars per hour. The item cost is the total cost of the product being evaluated, and the repair component cost is the cost of the parts required to repair a product. These categories can help the team determine whether it is cost effective to repair a part or to replace it. The final column is the output for the EFC. When using a spreadsheet that can perform calculations, the formula for EFC (Equation 3-8) should be used for automatic calculation as the input variables are added.



Failure Identification									
Input									Output
Life Cycle (Years)	Product Quantity (per year)	Probability of Failure	Repair Time (Hr)	Labor Rate ($/Hr)	Lost Opportunity Cost ($/Hr)	Item Cost ($)	Repair Component Cost ($)	External Failure Cost ($)	EFC ($)

Figure 3-10. EI-FMEA template, failure identification.

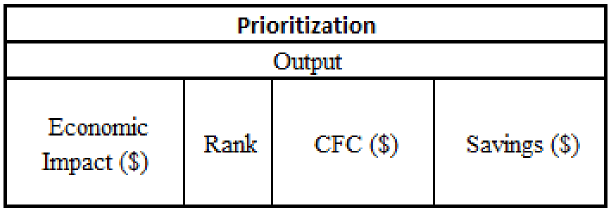
In the corrective action group (Figure 3-11), inputs are collected to determine the AFC. The corrective action is listed in the first column and is the plan to address the root cause. Next is the cost to implement the corrective action, the new probability of failure, the new repair time, and the new costs for the item and repair components with respect to the corrective action. The output from the corrective action is the recurring implementation cost (Equation 3-9) and the AFC (Equation 3-10).



Corrective Action							
Input						Output	
Improvement Plan / Corrective Action	Cost to Implement ($)	CA Probability of Failure	CA Repair Time (Hr)	CA Item Cost ($)	CA Repair Component Cost ($)	Recurring Implementation Cost ($)	AFC ($)

Figure 3-11. EI-FMEA template, corrective action.

The final group of the EI-FMEA template concerns prioritization. This group is often calculated automatically using formulas for the EIV (Equation 3-11) and the CFC (Equation 3-12). Then, the team evaluates the different failure modes and determines the impact of a corrective action. The rank of the EIV, which correlates to the largest potential savings, shows which failure modes should be addressed. For a given failure scenario or EI-FMEA spreadsheet, the total savings can be found by summing the negative-value EIVs.



Prioritization			
Output			
Economic Impact ($)	Rank	CFC ($)	Savings ($)

Figure 3-12. EI-FMEA template, prioritization.

3.8 Summary

The EI-FMEA is a dependability analysis method that minimizes failure cost through prevention techniques. EI-FMEA, a new methodology for performing failure mode and effects analysis, was created to address traditional FMEA's major limitation—ambiguity of the risk priority number and SOD variables (H.-C. Liu et al., 2013). The SOD variables in traditional FMEA are replaced by the probability of failure and the failure cost for a given failure mode. The RPN is replaced by the EIV metric which uses potential savings as the prioritization method for corrective action implementation. Using the EIV risk prioritization metric also addresses gaps in other failure-cost-based FMEAs (Kmenta & Ishii, 2005; Rhee, 2005) that rank risk based on the EFC. The EIV risk prioritization metric addresses the full economic impact by including the implementation cost and recurring costs associated with a corrective action. The EIV risk prioritization metric can also be used to allocate finite resources in a company. By ranking risk based on potential savings, the company understands where the allocation of resources will create the most cost-effective solution. This can help a company to be more agile, address waste in the system, reduce costs, and reduce cycle times, which can lead to a competitive advantage in the marketplace.

By replacing the SOD variables, RPN, and EFC as a risk prioritization metric, the EI-FMEA method addresses the major limitation of traditional and cost-based FMEA methods. Additionally, the EIV risk prioritization metric meets the following requirements for a new risk prioritization method:

1. A new risk prioritization method must have a decision-support system to determine when to implement a corrective action or improvement (H.-C. Liu et al., 2016);
2. Corrective actions or improvements should not be implemented if they are not economically sustainable (Carmignani, 2009; Cheah et al., 2011; Kmenta & Ishii, 2005).

CHAPTER IV

FAILURE COST AND PROBABILITY OF FAILURE ESTIMATION

This chapter will examine different methods for estimating failure cost and probability of failure. The chapter begins with a brief overview of the different methods available, followed by a detailed look at estimating cost and failure probabilities, and concludes with a summary.

4.1 Estimation Methods

The EI-FMEA method uses failure cost and the probability of failure as the main inputs for measuring the risk of a particular failure. As discussed previously, events are governed by randomness and uncertainty. There are multiple accepted ways to measure uncertainty, but users may not understand which ways are appropriate for the given circumstance. This chapter introduces some commonly used methods. The first part of this chapter focuses on failure cost estimation, including both internal and external failure costs. The second part focuses on probability of failure and lists multiple methods for estimating failure probability for different situations. By the end of the chapter, a collection of estimation techniques that support the EI-FMEA method is introduced.

4.2 Failure Cost

Failure cost, both internal and external, contains the repair cost, component cost, and lost opportunity cost. Internal failure cost is a product’s failure cost prior to its delivery to the final customer; external failure cost is a product’s failure cost after being received by the final customer (Juran & Godfrey, 1999). For example, in Figure 3-4, internal failures can be found at prototype testing, manufacturing inspection, or pre-delivery inspection life cycles, and external failures are found in the field during the operation life cycle. While component cost (Section 3.3.2) and lost opportunity cost (Section 3.3.3) are easier to estimate, estimating repair cost is more difficult.

4.2.1 Repair Cost

Repair cost is the product of the total repair time and the labor rate. The labor rate can be determined based on the wages of the personnel performing the repair. The repair time is the total time needed to return an item in a failed state back to its last known good condition (i.e., meeting the specification), including both the time needed to determine the root cause after a failure and the time to renew the product; repair time is the transition between the failure state and the repair state (Attar, Raissi, & Khalili-Damghani, 2017). The repair time distribution is often shown using the lognormal distribution due to the large amount of small repair times and small amount of large repair times (NASA, 2015). The repair time can be estimated in multiple ways such as empirical data, industry repair guides, and expert opinion.

4.2.1.1 Empirical Data

Empirical data can come from the test and operation repair times of the product being evaluated or from the repair data of a similar product in the same industry. This data can be gathered from a company’s quality system or build records. Finding the repair times in the quality system, however, can take a long time. Better record keeping makes finding the information easier. For a particular failure mode, the individual repair times can be collected over a time period to find the MTTR. MTTR is also called the expected repair time and is found by taking the mean of the individual repair times for a given failure (Birolini, 2014). The MTTR for a lognormal distribution is found using

Equation 4-1 while the lognormal variance is found using Equation 4-2.

Equation 4-1. Lognormal MTTR (from NASA (2015).

$$MTTR = \mu = e^{\left(\overline{t'} + \frac{s'^2}{2}\right)}$$

$where\ \overline{t'}\ is\ the\ maximum\ likelihood\ estimator\ (MLE) for\ the\ lognormal\ repair\ time\ mean\ and\ s'^2\ is\ the\ MLE\ for\ the\ lognormal\ repair\ time\ variance.$

Equation 4-2. Lognormal repair time standard deviation (from NASA (2015).

$$\sigma = MTTR\sqrt{e^{s'^2} - 1}$$

Equation 4-3. MLE repair time mean (from NASA (2015)).

$$\overline{t'} = \frac{1}{n}\sum_{i=1}^{n} t'_i$$

$where\ t'_i\ is\ the\ lognormal\ of\ repair\ time\ t_i, and\ n\ is\ the\ number\ of\ repair\ times.$

Equation 4-4. MLE repair time variance (from NASA (2015)).

$$s'^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(t'_i - \overline{t'}\right)^2$$

For example, during the assembly of an electric vehicle, an automated robot places the battery pack in the chassis. Over the past 3 months, the robot has failed 10 times, with the time (in hours) to repair each failure as 3.9, 11.7, 5.7, 4.2, 9.3, 4.5, 5.1, 7.1, 5.3, and 5.7. The MLE repair time mean is found using Equation 4-3; the lognormal values are found in Table 4-1. The result is a MLE repair time mean of 1.77.

Table 4-1. Lognormal Repair Times

Repair time (t_i)	**Lognormal repair time (t_i')**
3.9	1.36
4.2	1.44
4.5	1.50
5.1	1.63
5.3	1.67
5.4	1.69
5.7	1.74
7.1	1.96
9.3	2.23
11.7	2.46

The MLE repair time variance is found using Equation 4-4 and results in a value of 0.1235. The MTTR for the lognormal distribution of the battery installation robot is found using Equation 4-1 with a standard deviation found using Equation 4-2:

$$MTTR = e^{\left(1.77+\frac{0.1235}{2}\right)} = 6.23\ hours$$

$$\sigma = MTTR\sqrt{e^{s'^2}-1} = 6.23\sqrt{e^{0.1235}-1} = 2.26\ hours$$

4.2.1.2 Industry Repair Guides

Different industries have their own repair guides that list common failures and estimated repair times for products in operation. The repair guides can come from the manufacturer or independent agencies for a given product. They can take the form of manuals, software, or online databases. Repair guides are widely used in the automotive industry and have existed as early as the 1920s (Cortada, 2017). Today, most automotive vehicle manufacturers provide repair times for common failures to their authorized service centers and dealerships. Independent automotive repair facilities may use the manufacturer repair guides or a repair guide authored by an independent agency. A few of the more common sources for independent repair guides are Chiltons®, Mitchell 1®, and ALLDATA®. Guide authors find the estimated repair time by using subject matter experts (SME) and materials such as field data, time studies, and vehicle manufacturer data to determine how long an average mechanic requires to make a repair given average tools, average equipment, and an average vehicle (Hixson, 2013). These repair guides are available through a subscription service where new car models and repair times are constantly being added and updated.

Repair guides are also commonly used for warranty work. The original manufacturer is often associated with authorized repair centers that end users can contact to perform warranty work on the product. The warranty period is a given amount of time or use during which a manufacturer guarantees failure-free performance and pays to repair a product that has a failure during that period. Manufacturers typically provide estimated or maximum repair times to a repair center for normal repairs. The maximum time allowed is the time for which the manufacturer reimburses the repair center for performing the warranty work. For example, Delfield® is a company that manufactures refrigeration units and servings stations for the restaurant industry. Their standard labor guideline lists the amount of time to repair or replace certain components on their products, as shown in Table 4-2.

Table 4-2. Warranty Repair Time Guidelines

Standard Labor Guidelines to Repair or Replace Parts for Delfield® Products
Labor up to 1-hour to replace
- Infinite switch - Door jamb switch - Solenoid switch - Hi-limit/thermal protector switch - Fan delay/defrost termination switch - Compressor start components - Defrost timer - Thermometer - Gear motor - Contactor/relay - Transformer - Evaporator/condenser fan motor - Circulating fan motor and blade - Digital control - Water level sensor - Door hinges and locks - Condensate element - Springs/lowerator
Labor up to 2-hour to replace
- Thermostat - Drawer tracks - Pressure control - Solenoid valve - Defrost element - Heating element - Locate/repair leak
Labor up to 3-hour to replace
- EPR or CPR valve - Expansion valve - Condenser or evaporator coil - Cap tube
Labor up to 4-hour to replace
- Compressor

Note. Adapted from Johnson (2013).

4.2.1.3 Expert Opinion

Early in a product’s life cycle, detailed failure cost information is not often available. Repair times can be estimated by SMEs on the FMEA team. The team can choose multiple ways to estimate a repair time, from point estimates to Monte Carlo simulation. When using a point estimate, a team may determine a most likely repair time or give a minimum and maximum range value for the repair time. One disadvantage of using a SME opinion is subjectivity; and can be addressed by a Monte Carlo simulation along with the SME repair times to calculate an MTTR and standard deviation. With limited empirical information and SME-estimated repair times, the triangular distribution provides a basis for performing a Monte Carlo simulation (Rhee, 2005). A triangular distribution has three variables: minimum, most likely, and maximum repair times. For example, the repair time of a composite wing on an aircraft can take a minimum of 4 hours and a maximum of 16 hours with a most likely time of 8 hours. To estimate the MTTR and standard deviation of the repair time for the composite wing, a Monte Carlo simulation is used. There are multiple commercially available software programs that can randomly generate values based on a probability density function. For this study, I use JMP® statistical software. A Monte Carlo simulation is beneficial because it allows users to run multiple random number generations for estimation purposes. The triangular distribution of (4, 8, and 16) with 10,000 replicates produces the distribution shown in Figure 4-1, with a lognormal curve fitted over the plot. Fitting the lognormal curve creates a quick visual aid to determine if the values for the triangular distribution are close to a lognormal curve as repair times are typically lognormal (NASA, 2015). The lognormal curve is not expected to fit the triangular distribution perfectly, but the triangular distribution should be adjusted if the values are skewed to the right or left. According to Equation 4-1 and Equation 4-2, the MTTR and the standard deviation for the composite wing repair is 9.35 hours and 2.61 hours, respectively.

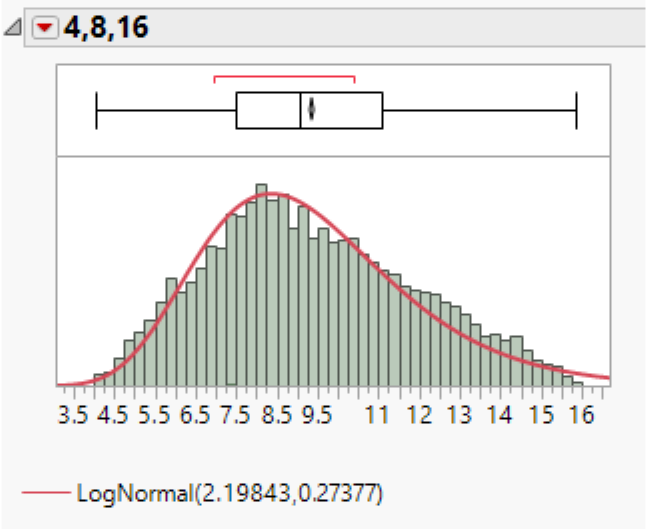


Figure 4-1. Histogram plot for composite wing repair times.

4.3 Probability of Failure

Reliability is the probability that a product meets its specification over a period of time or demand; risk is the probability that a product does not meet its intended specification (Birolini, 2014). Reliability is also known as the probability of success while risk is also known as the probability of failure. Reliability is shown mathematically by Equation 4-5.

Equation 4-5. Reliability equation.

$$1 = R(t) + F(t)$$

$where\ R(t)\ is\ the\ reliability\ and\ F(t)\ is\ the\ risk.$

The probability of failure and the failure rate must be defined to understand how each is used in reliability engineering. The probability of failure and the failure rate are not the same and should not be used interchangeably. One way to measure the probability of failure is to measure on a demand base using results from a binominal distribution where each test is independent and results in a pass or fail (Quigley & Revie, 2011). For example, a battery in a car is used to start the car. The battery is considered successful if the car starts and is considered a failure if the car does not start. The formula for the probability of failure is shown in Equation 3-1.

The failure rate is typically a time-based measure of an item using a Weibull or exponential distribution where an item failure count is measured over a run time (Adams, 2017). For example, a clock is used to measure time. The total run time of the clock is measured before the clock can no longer accurately measure the time. The failure rate is denoted by the Greek letter lambda (λ), and the formula for failure rate is shown in Equation 4-6.

Equation 4-6. Failure rate (from Adams (2017).

$$Failure\ rate = \lambda = \frac{n(f)}{T}$$

$where\ n(f)\ is\ the\ failure\ count\ and\ T\ is\ the\ total\ run\ time.$

In reliability engineering, a large sample population with independent and statistically identical items experiences a failure rate over a time curve that appears u-shaped, which is often called a bathtub curve. In the bathtub curve, the initial life has a decreasing failure rate, the middle portion has a constant failure rate, and the end of life experiences an increasing failure rate (Birolini, 2014).

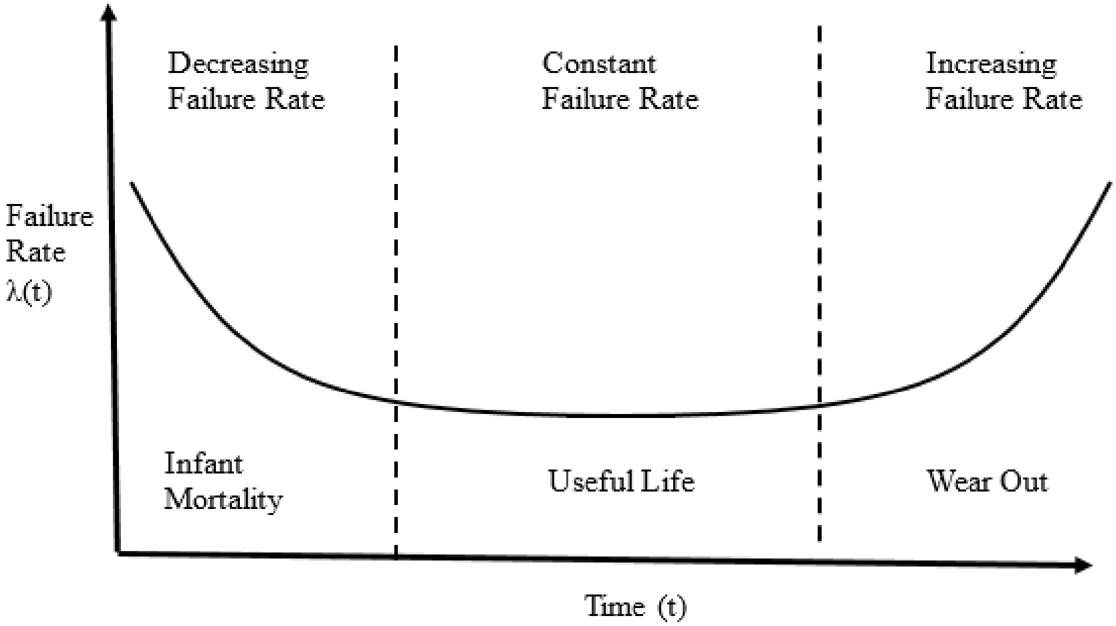


Figure 4-2. Bathtub reliability curve. Adapted from Rhee (2005).

The initial life is also known as the infant mortality, where failures are due to random failures in components and processes (Birolini, 2014). During the transition to production, the product is refined, and processes become mature through development cycles, component burn-in, and incoming inspections. The failure rate is constant through the useful life of the product and is the longest time period of the life cycle. By the end of the life cycle, the failure rate begins to increase due to fatigue and worn-out components. The bathtub curve can be modeled by the failure rate for the Weibull distribution. Table 4-3 shows the relation between the Weibull shape parameter and the slope of the failure rate over time.

Table 4-3. Weibull Failure Rate Versus Shape Parameter

Shape parameter	Failure rate	Life cycle
$0 < \beta < 1$	Decreasing	Infant
$\beta = 1$	Constant	Useful life
$\beta > 1$	Increasing	Wear out

Note. Adapted from Assis, Borges, and Vieira de Melo (2013).

To find the probability of failure, the Weibull distribution is used (Equation 4-7).

Equation 4-7. Weibull probability of failure.

$$F(t) = 1 - e^{-(\lambda t)^{\beta}}$$

$where\ t\ is\ time, \beta > 0\ and\ is\ the\ shape\ parameter,$

$and\ 0 \leq \lambda \leq 1\ and\ is\ the\ failure\ rate.$

When the shape parameter is equal to 1, the Weibull distribution is the same as the exponential distribution (Equation 4-8).

Equation 4-8. Exponential probability of failure.

$$F(t) = 1 - e^{-(\lambda t)}$$

The probability of failure is commonly shown using the exponential distribution for simplification when small amounts of data are available, but this can lead to overestimating and underestimating of the failure rate (J. B. Bowles, 2002). Choosing the appropriate method to determine the failure rate is the user's responsibility.

4.3.1 Empirical Data

The empirical failure rate data can come from a product's test and operational history or from a similar product history. This information can be gathered from a company's quality system or build records.

4.3.1.1 Data Center Example

Backblaze is a cloud computing storage company that houses a data center with thousands of individual hard disk drives (HDD) and over 300 petabytes of storage capacity. Each day, Backblaze records the operating parameters of the individual HDDs in the data center and monitors for failures. Summarizing the daily records for 2016 by model type of HDD yields the following failure count and other metrics shown in Table 4-4.

Table 4-4. HDD Failures for 2016

MFG	Model	HDD Size (TB)	HDD Count	Average Age (months)	HDD days	HDD failures
HGST	HUH728080ALE600	8	45	23	16,155	0
Seagate	ST8000DM002	8	8,660	5	1,075,720	48
Seagate	ST800NM0055	8	60	1	1,560	0
Seagate	ST6000DX000	6	1,889	21	684,840	16
WDC	WD60EFRX	6	446	24	166,152	25
Toshiba	MD04ABA500V	5	45	22	16,425	1
HGST	HDS5C4040ALE630	4	2,625	45	987,011	14
HGST	HMS5C4040ALE640	4	7,014	29	2,579,698	28
HGST	HMS5C4040BLE640	4	9,407	16	2,436,130	34
Seagate	ST4000DM000	4	34,738	22	12,359,750	938
Seagate	ST4000DX000	4	184	39	72,615	27
Toshiba	MD04ABA400V	4	146	21	52,983	0
WDC	WD40EFRX	4	75	17	16,790	1
HGST	HDS5C3030ALA630	3	4,476	56	1,647,137	34
HGST	HDS723030ALA640	3	978	61	361,937	22
Toshiba	DT01ACA300	3	46	44	16,900	2
WDC	WD30EFRX	3	1,105	30	390,379	35
		Total	**71,939**		**22,882,182**	**1,225**

Note. Adapted from (Klein, 2017a).

From this data, the probability of failure can be estimated, and a failure rate per HDD model can be established. Using Equation 3-1, the probability of failure for each model can be found by dividing the HDD failure count by the HDD count for that model. The failure rate is found using Equation 4-6, where the HDD failure count is divided by the HDD days. This produces a failure rate per day for a given HDD. To find an annual failure rate, the per-day failure rate is multiplied by 365. Table 4-5 shows the results of the individual failure rates and the probability of failures.

Table 4-5. HDD Annual Failure Rate and Probability of Failure

MFG	**Model**	**HDD Count**	**HDD days**	**HDD failures**	**λ (annual)**	p_f
HGST	HUH728080ALE600	45	16,155	0	0.0000	0.0000
Seagate	ST8000DM002	8,660	1,075,720	48	0.0163	0.0055
Seagate	ST800NM0055	60	1,560	0	0.0000	0.0000
Seagate	ST6000DX000	1,889	684,840	16	0.0085	0.0085
WDC	WD60EFRX	446	166,152	25	0.0549	0.0561
Toshiba	MD04ABA500V	45	16,425	1	0.0222	0.0222
HGST	HDS5C4040ALE630	2,625	987,011	14	0.0052	0.0053
HGST	HMS5C4040ALE640	7,014	2,579,698	28	0.0040	0.0040
HGST	HMS5C4040BLE640	9,407	2,436,130	34	0.0051	0.0036
Seagate	ST4000DM000	34,738	12,359,750	938	0.0277	0.0270
Seagate	ST4000DX000	184	72,615	27	0.1357	0.1467
Toshiba	MD04ABA400V	146	52,983	0	0.0000	0.0000
WDC	WD40EFRX	75	16,790	1	0.0217	0.0133
HGST	HDS5C3030ALA	4,476	1,647,137	34	0.0075	0.0076
HGST	HDS723030ALA	978	361,937	22	0.0222	0.0225
Toshiba	DT01ACA300	46	16,900	2	0.0432	0.0435
WDC	WD30EFRX	1,105	390,379	35	0.0327	0.0317
				Total	**0.0195**	**0.0170**

Note. Adapted from (Klein, 2017a).

In order to convert the annual failure rate to a probability of failure, the failure rate is assumed to be constant, and Equation 4-8 is used to find the probability of failure for t=1 (1 year) for a failure rate of 0.0195, which gives the following result:

$$F(t) = 1 - e^{-(\lambda t)} = 1 - e^{-(0.0195*1)} = 0.0193$$

The differences in the probability of failure can be attributed to the assumption of a constant failure rate. In the average age of the HDD in Table 4-4, there is a range in age which could be masking an increased failure rate during the infant or wear-out period of a HDD. When choosing a probability of failure for the EI-FMEA, the user decides which value is more appropriate to use.

If the failure rate is used, it should be normalized to an annual failure rate by using either Equation 4-7 or Equation 4-8 with a time period of 1.

4.3.2 Component Manufacturer Data

A manufacturer can report reliability data for a product by giving a mean time to failure (MTTF). The MTTF is the expected time a product will run before a failure event occurs, assuming a constant failure rate while being non-repairable. The MTTF can be found by dividing the total run time of a number of products and by the number of failures (Equation 4-9). Using Equation 4-9, the MTTF is the reciprocal of the failure rate (Equation 4-6).

Equation 4-9. Mean time to failure.

$$MTTF = \frac{T}{N_T} = \frac{1}{\lambda}$$

$where\ T\ is\ the\ cumulative\ run\ time\ and\ N_T\ is\ the\ is\ the\ observed\ number\ of\ failures$

$by\ time\ T.$

When a company wants to report a MTTF for their product, they often perform a case study on a sample set of a product. For example, an internet service provider wants to determine the MTTF for their cable modem. They take a sample set of 50 modems and run them continuously for 60 days (1440 hours). During the test duration, 1 modem fails. Using Equation 4-9, the company reports the MTTF for the modem as 72,000 hours or 8.22 years.

$$MTTF = \frac{1440\ hr * 50\ modems}{1} = 72{,}000\ hr$$

To determine the probability of failure using the manufacturer's MTTF value, Equation 4-8 needs to be modified resulting in Equation 4-10.

Equation 4-10. Exponential probability of failure with MTTF.

$$F(t) = 1 - e^{-\left(\frac{t}{MTTF}\right)}$$

The probability of failure for the cable modem is shown for the product life in Table 4-6.

Table 4-6. Modem Probability of Failure

Run time (years)	**p(f)**
1	0.11
2	0.22
3	0.31
4	0.39
5	0.46
6	0.52
7	0.57
8	0.62
9	0.67
10	0.70

4.3.3 Industry Reliability Standards

Industry reliability guides and standards are issued by companies, government agencies, and independent organizations to help individuals estimate reliability through the identification of physical and environmental factors exerted on a product. A list of the major reliability standards is shown in Table 4-7.

Table 4-7. Major Reliability Estimation Guides and Standards

Standard	Year	Product Type
FIDES Guide 2009-A	2010	Electronics
MIL-HDBK-217F	1995	Electronics
NSWC-11	2011	Mechanical Equipment
Telcordia SR-322, Issue 4	2016	Telecommunication

The FIDES methodology was created in response to the lack of updates on MIL-HDBK-217F and can be used in all industries using electronics including, for example, aerospace, military, automotive, railway, space, telecommunications, and household electronics (FIDES, 2010). The FIDES consortium is comprised of commercial and military partners. In the guide, the general reliability model is based on the failure rate where the failure rate is the summation of physical contributions multiplied by the product of process contributions (Equation 4-11).

Equation 4-11. FIDES general failure rate model (from FIDES (2010))

$$\lambda_i = \sum \lambda_{Physical} * \Pi_{PM} * \Pi_{Process}$$

$where\ \lambda_{Physical}\ is\ the\ physical\ failure\ rate, \Pi_{PM}\ is\ the\ mulitplication\ factor\ for\ quality$
$control\ over\ the\ part\ manufacturing, and\ \Pi_{Process}\ is\ the\ multiplication\ factor\ for$
$the\ usage\ process\ for\ the\ product.$

The estimated failure rates are represented in FIT, where 1 FIT is equal to 1 failure per billion hours (FIDES, 2010).

MIL-HDBK-217 estimates failure rates based on part stress analysis and includes factors for electronic components such as semiconductors, lasers, tubes, resistors, capacitors, inductive devices, relays, fuses, conductors, and switches (United States Department of Defense, 1991).

The part failure rate model consists of the base part failure rate multiplied by the π factors which modify the base failure rate for environmental conditions and other parameters that affect the reliability of the part (United States Department of Defense, 1991).

Equation 4-12. MIL-HDBK-217 failure rate (from United States Department of Defense (1991)).

$$\lambda_p = \lambda_b * \pi_T * \pi_A * \pi_R * \pi_S * \pi_C * \pi_Q * \pi_E$$

$where\ \lambda_b\ is\ the\ base\ failure\ rate, \pi_T\ is\ the\ temperature\ factor, \pi_A\ is\ the\ application\ factor, \pi_R\ is\ the\ power\ rating\ factor, \pi_S\ is\ the\ electrical\ stress\ factor,$

π_C *is the contact construction factor,* π_Q *is the quality factor, and* π_E *is the*

$the\ operating\ environment\ factor.$

The Naval Surface Warfare Center, looking to expand reliability estimation beyond electronic components, created a reliability estimation method for mechanical equipment. The method uses a similar approach to MIL-HDBK-217 by estimating failure rates based on the product of a base failure rate and the environmental, stress, and operating factors. The Naval Surface Warfare Center 11 (NSWC-11) handbook includes estimation methods for seals, gaskets, springs, solenoids, valve assemblies, bearings, pumps, compressors, electronic motors, brakes, clutches, and other mechanical equipment.

The different estimation techniques in the various industry standards and guides help estimate a constant failure rate for a product, which can be used with Equation 4-6 to determine the product's probability of failure.

4.3.4 Expert Opinion

Early in the product's life cycle, a mature design is not available. A part list or bill of materials may not be fully developed, nor may a suitable similar empirical database be available. During this time, the engineers and other SMEs may be required to use engineering judgment for potential failure rates of a product. The SMEs may choose to estimate a probability of failure (e.g., 1 in 50,000 cycles) or estimate the MTTF (e.g., 50,000 hours). When estimating a MTTF, either a point estimate or Monte Carlo simulation may be used, similar to the method shown in Section 4.2.1.3 where the MTTF is an exponential distribution. To convert the MTTF to a failure rate and find the probability of failure, a constant failure rate must be assumed.

Another appropriate method is based on low- or zero-failure-rate empirical data. In a study comparing multiple methods for estimating the probability of failure when the empirical data has zero failures, Bailey (1997) identifies an appropriate equation that provides the probability of failure based on the number of trials preformed with zero failures.

Equation 4-13. Zero failure estimator (from Bailey (1997)).

$$P = 1 - 1.5^{\frac{1}{n}}$$

$where\ \ P\ is\ the\ probability\ of\ failure\ on\ a\ particular\ trial\ and\ n\ is\ the\ number\ of\ trials\ performed\ with\ zero\ failures.$

Equation 4-13 can be used by the SME for determining the probability of failure for a given period of trials or for a given time period.

4.4 Variability in Failure Cost and Probability of Failure

Variability in the failure cost calculation can come from the repair time and the probability of failure estimation methods. A way to incorporate the variability into the calculation can be done using empirical data or Monte Carlo simulation.

4.4.1 Empirical Data

Failure data is collected for a theoretical power supply during a built-in-test that records the ability of the power supply to perform after being subjected to a series of temperature cycles. The number of failures is recorded along with the amount of time it takes to repair and retest the unit to pass the test and is shown in Table 4-8.

Table 4-8. Power Supply Failures

Failure Number	**Repair Time (hr)**	**Failure Number**	**Repair Time (hr)**
1	5.46	11	4.11
2	5.10	12	5.52
3	4.21	13	5.87
4	5.74	14	6.70
5	4.86	15	5.37
6	4.30	16	3.68
7	4.39	17	5.32
8	6.57	18	5.44
9	4.56	19	4.38
10	5.67	20	3.93

There are 500 power supplies tested with 20 failures recorded. Calculating the expected failure cost for the power supply with a quantity of 500, a labor rate of $160/hr, repair component cost of $200, and a failure rate of 0.04 (i.e., 20/500) yields 20 different failure costs for the power supply failure. Calculating the 1st and 3rd quartiles shows the interquartile range that encompasses the middle half of the failure cost which is $17,811 - $22,031. Visually, this can be expressed using a box and whisker plot where the box is the 1st and 3rd interquartile range and the whiskers show the top and bottom failure cost (Figure 4-3). The interquartile range is one way to bound the EFC variability due to repair time from the power supply test.

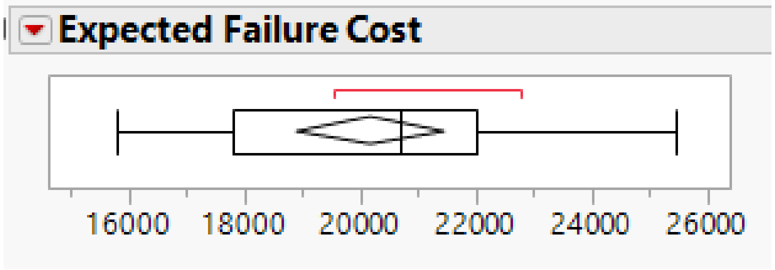


Figure 4-3. Power supply EFC box plot

4.4.2 Monte Carlo Simulation

The variability when estimating a failure cost can be included through the use of a Monte Carlo simulation. Variability can come from probability of failure and the repair time for a given failure mode. A theoretical radar system has an acceptance test to test the alignment of the antenna. If the alignment fails, the radar test technician performs an alignment procedure that can vary in the time to perform with a triangular distribution of 2, 3, or 6 hours. A radar system has a normal probability of failure distribution of 0.01 with standard deviation of 0.000001 and a repair time triangular distribution of 2, 3, and 6 hours. A Monte Carlo simulation is performed to generate 1,000 random values for the probability of failure and the repair time. Calculating the EFC using the 1,000 replicates for probability of failure and the repair time, a quantity of 10,000 radar systems, and a labor rate of $160/hr gives a range of potential EFC. The 1st and 3rd quartiles provides the interquartile range $47,805 - $67,885 for the estimated EFC. Visually this is shown using a box and whisker plot to include the top and bottom EFC values shown in Figure 4-4 and can be used to account for variability by bounding the EFC compared to a single point estimate.

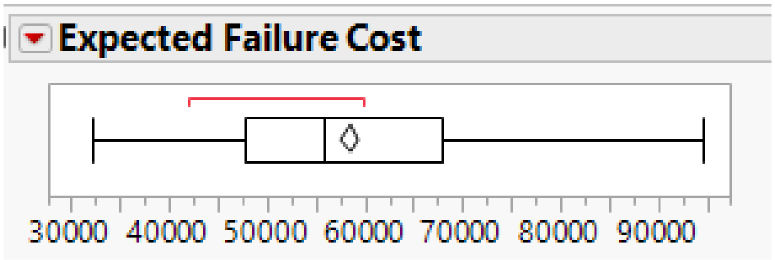


Figure 4-4. Radar system Monte Carlo EFC box plot

The EI-FMEA team determines which method is more appropriate for the given application when expressing EFC as a single point estimate or using a range that can be bounded by the 1st and 3rd quartiles.

4.5 Summary

In this chapter, a variety of estimation methods are introduced for determining the failure cost and the probability of failure, which can be used during the EI-FMEA process. No single estimation method addresses all situations that may be encountered. A combination of the methods is most often needed during an EI-FMEA. When to use each method is decided by the EI-FMEA team, but there are times when certain methods increase the accuracy of the results. Empirical test data can provide actual repair times and reliability estimates, but they may not be available in the early life cycle of a product. During product development and early production, the use of industry repair guides, component manufacturer data, and industry reliability standards can fill these gaps while an empirical test database is collected. At product inception, when a product has a limited component list or bill of materials, using SMEs to provide inputs can be invaluable. While SME opinion is the least accurate of the methods described, it may be the only option at the time; however, using the Monte Carlo simulation to generate random data can help with the subjectivity that can come from varying expert opinions. An FMEA team can choose to use point estimates or a range of failure costs by including the variability of the inputs used in the quartile examples.

CHAPTER V

FMEA METHOD COMPARISON

In this chapter, I perform three different FMEAs on the same product and compare the risk prioritization for the individual failure modes. The three methods being compared are traditional FMEA, Lifecycle Cost Based FMEA, and Economic Impact FMEA. The product being evaluated, which I refer to as *Product X*, is a ceramic matrix composite (CMC) product used in the aerospace industry. The chapter first introduces the three methods and describes Product X. Then, I perform the individual FMEAs, prioritize the risks, and present the top risks for each method. The chapter concludes with an evaluation of the three FMEA methods' ability to prioritize risk.

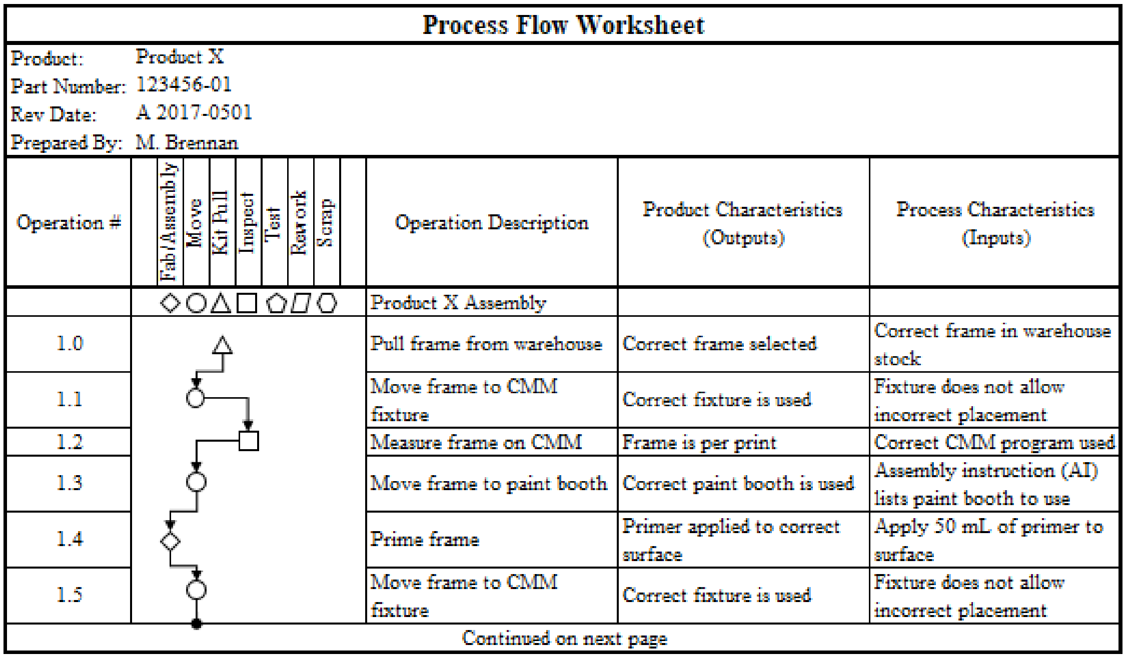
5.1 FMEA Methods

The three FMEA methods prioritize risk differently. In traditional FMEA, the RPN is found by taking the product of the SOD variables and the risk is ranked by aligning the RPN in descending order. The FMEA team then addresses the failure modes with the highest RPN values. In LCB-FMEA, the risk prioritization comes from ranking the EFC in descending order. The EFC is the product of the probability of failure, the cost of failure occurring, and the number of parts affected by the failure mode. The decision to implement a corrective action is based on cost effectiveness. The EI-FMEA method uses the EIV to prioritize risk. The EIV is ranked in ascending order, where higher-ranked values indicate higher savings in relation to the adjusted failure cost.

5.2 Product X

Product X is a CMC product used in the aerospace industry as an access cover that creates a seal on an airframe. The product is made of a CMC cover bonded into an exterior frame. The frame is used for mounting and to provide a seal surface on an airframe. It also has a structural component due to a variable internal pressure and must meet an internal burst pressure requirement. It is a relatively new product and is currently transitioning from development to production. The development build rate was approximately 30 units per year while the full production build rate is approximately 150 units per year. The expected production life cycle of the product is 10 years.

During development, failures were recorded over a 3-year period. This database is stored in the manufacturer's operating system and can be used to gather information for the FMEA process. There are 30 unique process steps in the build flow (Figure 5-1).



Process Flow Worksheet

Product: Product X
Part Number: 123456-01
Rev Date: A 2017-0501
Prepared By: M. Brennan

Operation #	Fab/Assembly	Move	Kit Pull	Inspect	Test	Rework	Scrap		Operation Description	Product Characteristics (Outputs)	Process Characteristics (Inputs)
	◇	○	△	□	⬠	▱	⬡		Product X Assembly		
1.0			△						Pull frame from warehouse	Correct frame selected	Correct frame in warehouse stock
1.1		○							Move frame to CMM fixture	Correct fixture is used	Fixture does not allow incorrect placement
1.2				□					Measure frame on CMM	Frame is per print	Correct CMM program used
1.3		○							Move frame to paint booth	Correct paint booth is used	Assembly instruction (AI) lists paint booth to use
1.4	◇								Prime frame	Primer applied to correct surface	Apply 50 mL of primer to surface
1.5		○							Move frame to CMM fixture	Correct fixture is used	Fixture does not allow incorrect placement

Continued on next page

Continued from previous page

1.6	□	Measure primer thickness on CMM	Correct primer thickness	Correct CMM program used
1.7	○	Move frame to assembly jig	Correct fixture is used	Fixture does not allow incorrect placement
2.0	△	Pull CMC raw cover from warehouse	Correct cover selected	Correct cover in warehouse stock
2.1	○	Move CMC to light table	Correct fixture is used	Fixture does not allow incorrect placement
2.2	□	Inspect CMC for defects	CMC meets defect criteria	Minimum acceptable defect criteria listed on print
2.3	○	Move CMC to coating jig	Correct fixture is used	Fixture does not allow incorrect placement
2.4	◇	Apply paint	Correct paint application	Spray gun setup per AI, application of 100 mL of paint to exterior surface
2.5	◇	Cure paint	Paint cured to AI	Correct cure profile selected
2.6	○	Move CMC cover to assembly jig	Correct fixture is used	Fixture does not allow incorrect placement
3.0	△	Pull adhesive kit from freezer	Correct adhesive kit selected	Correct adhesive kit in freezer
2.7	◇	Orient adhesive kit on frame	Adhesive located in correct position	Adhesive location documented in AI
2.8	◇	Assemble CMC cover to frame	CMC cover located to frame bond region	Fixture does not allow incorrect placement
2.9	○	Move assembly jig with Product X to oven	Correct oven is used	AI lists allowed ovens
2.10	◇	Cure Product X assembly	Assembly cured	Correct cure profile selected
2.11	○	Move Product X to paint booth	Correct fixture is used	Fixture does not allow incorrect placement
2.12	◇	Apply interior paint	Correct paint application	Spray gun setup per assembly instruction (AI), application of 50 mL of paint to interior surface
2.13	◇	Cure paint	Paint cured to AI	Correct cure profile selected
2.14	○	Move to metrology table	Correct fixture is used	Fixture does not allow incorrect placement
2.15	□	Measure dimensions	Correct dimensional requirements	Correct measurement profile is selected
2.16	○	Move to test fixture	Correct test fixture is used	Fixture does not allow incorrect placement
2.17	⬠	Perform seal test	Product X meets leak requirement	Correct test profile selected
2.18	⬠	Perform burst pressure test	Product X meets burst pressure requirement	Correct test profile selected
2.19	◇	Package for shipping	Product X ready for shipment	Correct packaging selected
2.20	○	Send to stock	Product X in queue for customer delivery	Assembly paperwork closed out correctly

Figure 5-1. Product X process flow worksheet.

5.3 Comparison of FMEA Methods

In the following sections, I perform an FMEA on Product X using traditional FMEA, LCB-FMEA, and EI-FMEA. The purpose of performing the FMEA on Product X is to improve the product's quality by identifying and ranking risk while prioritizing failure modes and corrective actions to reduce the expected failure cost. The failure modes identified by each of the risk prioritization methods are shown along with the ability of each method to reduce failure cost.

5.3.1 Traditional FMEA Results

To begin the traditional FMEA process, which I will refer to as FMEA, the FMEA team creates a list of failure modes. There are 63 potential individual failures from Product X identified by reviewing the quality records and brainstorming potential failure scenarios. Next, the team chooses SOD variable scales which are shown in Table 5-1, Table 5-2, and Table 5-3.

Table 5-1. FMEA Severity Factors

Severity of effect	**Severity ranking**
Product, end user, or plant safety at risk; risk of noncompliance to government regulations	**10**
Major impact on ability to produce quality product on time; includes significant interference with subsequent steps or damage to equipment; could result in mission failure	**9**
Product defect, rejection, failure in in-spec storage/operational environments; disruption to subsequent process steps	**7–8**
End-user dissatisfaction, some degradation in performance, loss of margin, or delays in the process	**4–6**
Slight end-user annoyance, slight deterioration in performance or margin, minor rework action, or in-line delays	**2–3**
Little to no effect on product or subsequent steps	**1**

Note. Adapted from Childs et al. (2012).

Table 5-2. FMEA Occurrence Factors

Occurrence defect rate	Occurrence ranking
1 in 2	**10**
1 in 8	**9**
1 in 20	**8**
1 in 40	**7**
1 in 80	**6**
1 in 400	**5**
1 in 1,000	**4**
1 in 4,000	**3**
1 in 20,000	**2**
1 in 1,000,000	**1**

Table 5-3. FMEA Detection Factors

Likelihood of detection	Detection ranking
No means of detection; no process or equipment to find problem in time to affect outcome	**10**
Controls would probably not detect defect; operator to perform self-inspection	**9**
Controls have poor chance of detecting defect; inspection alone to detect problem	**7–8**
Controls might detect defect; double inspection or inspection with equipment aids	**5–6**
Controls have good chance of detecting defect; process equipment detects presence of problem under most circumstances	**3–4**
Controls will almost certainly detect defect; process detects defects automatically	**1–2**

Note. Adapted from Childs et al. (2012).

For the individual failure modes, the SOD variables are chosen from the given tables, and the RPN is calculated for each failure mode. When performing an FMEA, the FMEA team chooses the level at which to address a particular failure mode. For Product X, that value is any RPN equal to or greater than 100. Of the 63 failure modes, there are 31 unique RPN values—29 above 100 and 34 below 100 (Figure 5-2).

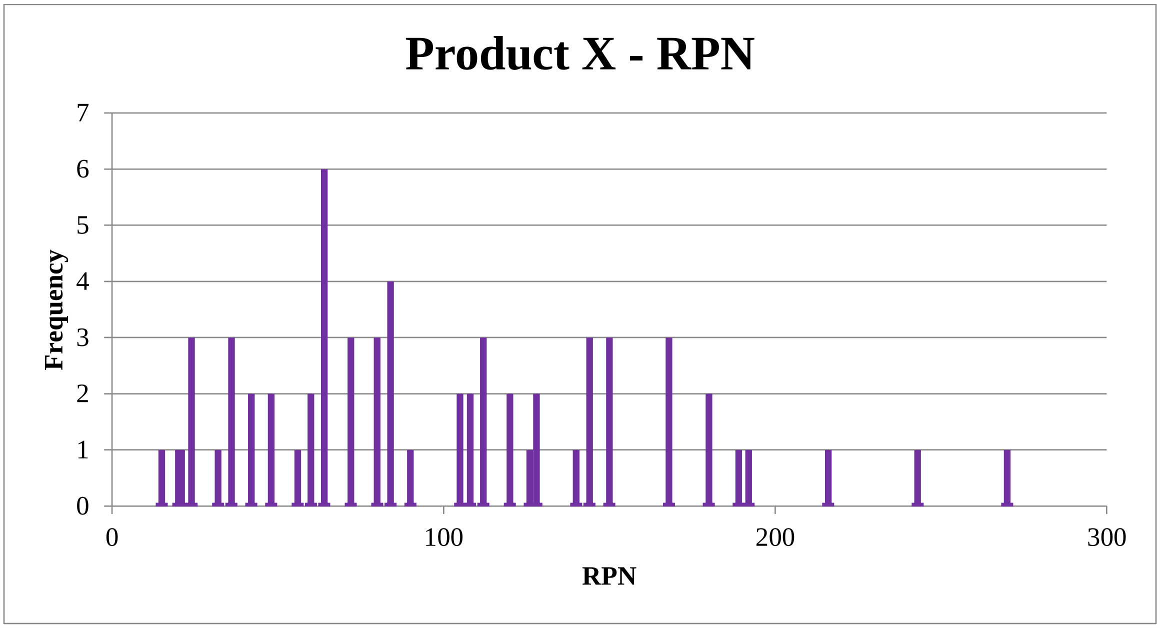


Figure 5-2. Product X RPN.

The top failure modes (Figure 5-3) are due to cracks occurring in Product X during manufacturing and operation. The higher RPN values occur during operation, where the likelihood of detection decreases significantly from the manufacturing cycle. In-process tests during manufacturing increases the likelihood of detection; cracks that develop in Product X in operation have a minimal chance of being discovered prior to a failure event.

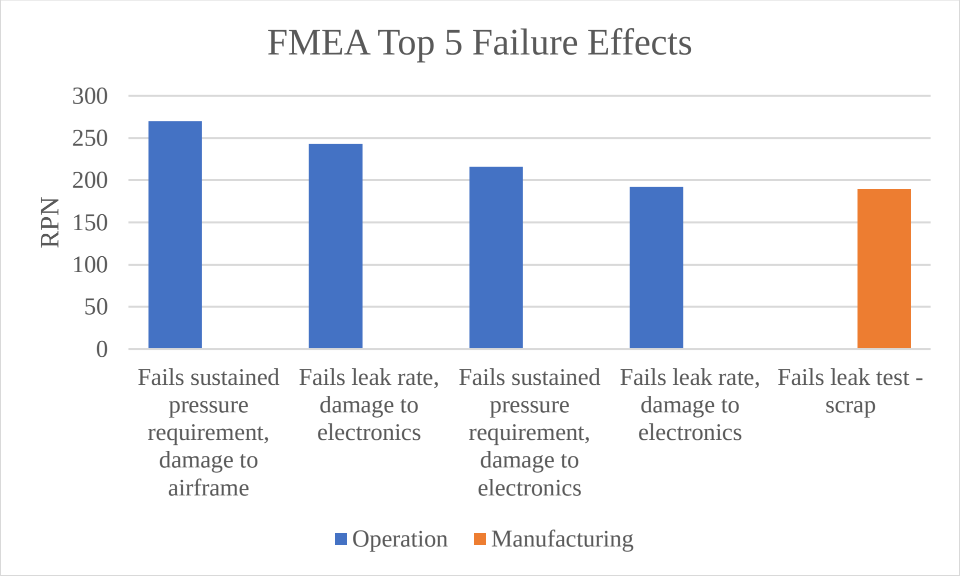


Figure 5-3. FMEA top 5 failure effects.

Failure modes are listed by item numbers 1 through 63 and Figure 5-4 shows their risk rank, where 1 is the highest risk, found by the RPN decision metric.

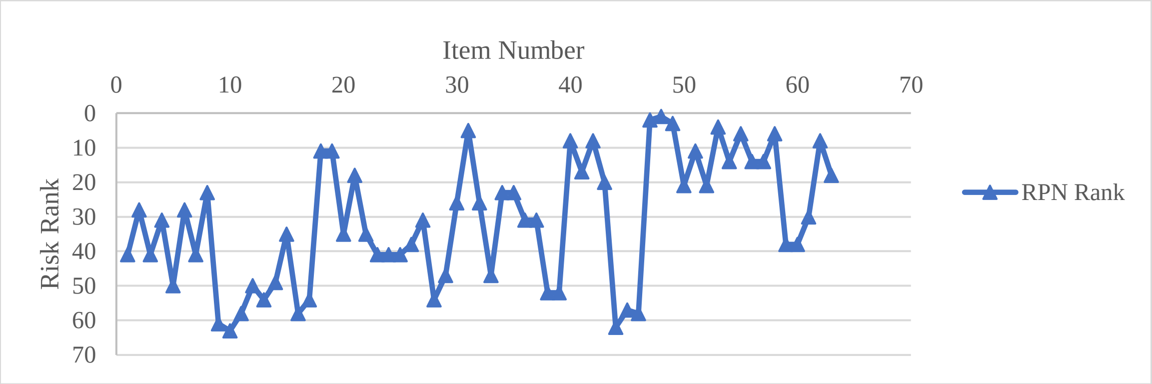


Figure 5-4. FMEA failure mode item number versus risk rank.

5.3.2 Lifecycle Cost Based FMEA Results

The LCB-FMEA uses the same set of failure modes and effects from the traditional FMEA method. To calculate the expected failure cost for each potential failure mode, Product X's build quantity, repair time, labor rate, and probability of failure need to be calculated. The manufacturer's quality system provides the failure rates, failure types, repair times, and other build information needed for the LCB-FMEA. A combination of empirical data, industry reliability standards, and SME input provides the input variables for the LCB-FMEA. Product X's total development build quantity over 3 years is 91 units with 57 individual failure events recorded. The probability of failure for a recorded failure event is found using Equation 3-1. For example, Product X has a requirement to sustain an internal pressure value with a maximum leak rate of y. A failure occurs when the leak rate of y is not met. Failing the leak test can occur when the interior surface of Product X is not thoroughly cleaned prior to the application of interior paint. Leak rate failure is the most common failure occurrence during the development life cycle, with 20 recorded instances. Therefore, the probability of failure is 20/91=0.2198.

There are multiple failure modes that have not occurred in Product X's development cycle and are not part of the industry reliability standards. To estimate probability of these failures, Equation 4-13, along with the life cycle of Product X and SMEs, is used. Product X's production rate is 150 units per year, with a life cycle of 10 years. The probability of failure is estimated on a yearly basis (Figure 5-5). The SME can then use the probability of failure for a given time period in the LCB-FMEA.

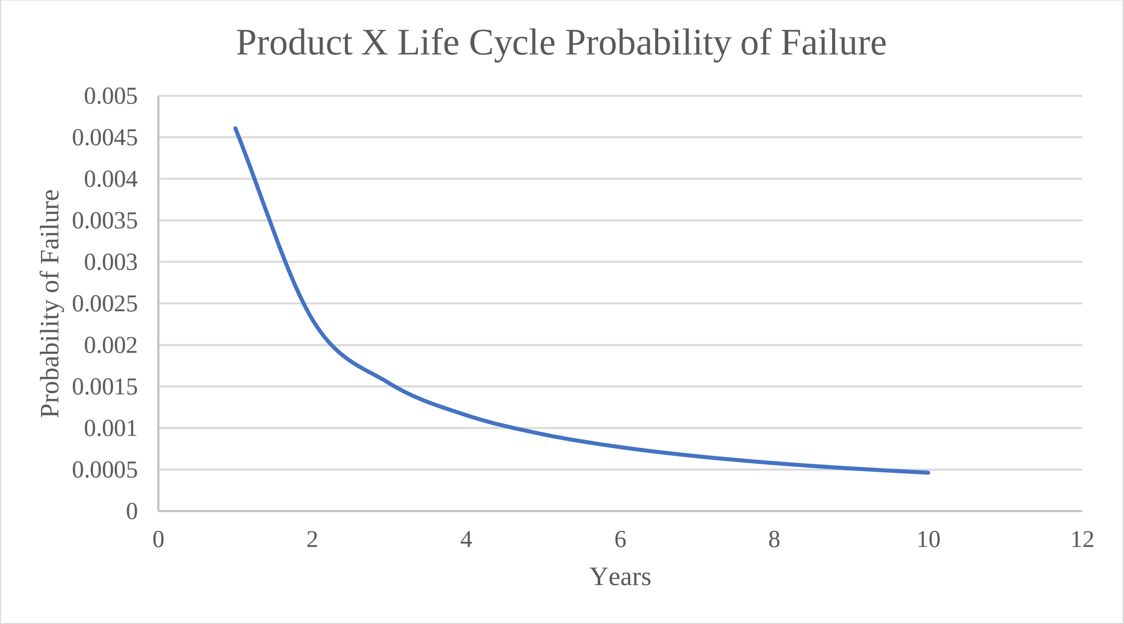


Figure 5-5. Product X’s estimated probability of failure.

Failure modes are listed by item numbers 1 through 63 and Figure 5-6 shows their risk rank, where 1 is the highest risk, is based on the EFC decision metric. For the LCB-FMEA method, there is a total EFC of $6,334,854.54 for Product X over its 10-year life cycle.

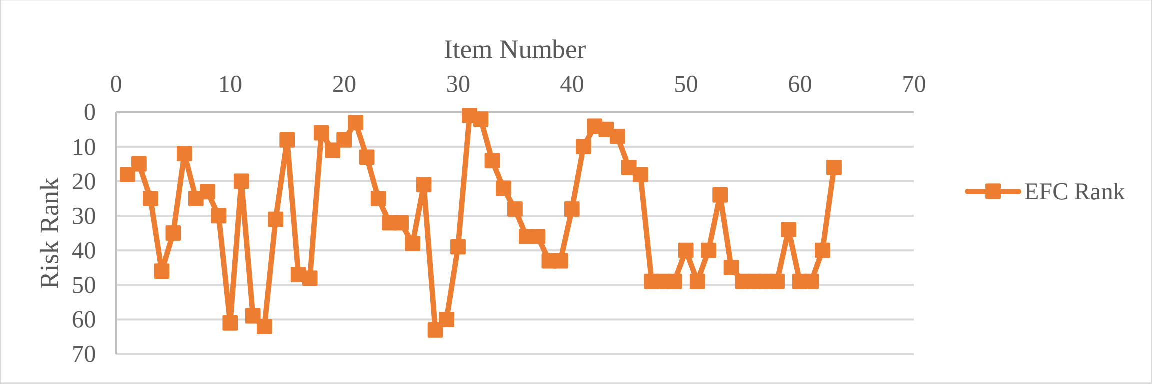


Figure 5-6. LCB-FMEA failure mode item number versus risk rank.

5.3.3 Economic Impact FMEA Results

EI-FMEA's methodology is similar to LCB-FMEA's. The two methods diverge in the risk prioritization of failure modes. This divergence happens after the EFC for the individual failure modes is calculated. The second portion of the EI-FMEA involves brainstorming corrective actions along with implementation cost, new probability of failure, new repair cost, new component cost, and new repair component cost. This is where the FMEA team determines the economic impact of implementing a corrective action on a failure mode and prioritizes based on the largest economic impact (i.e., cost savings). The EI-FMEA is unique in that it only ranks failure modes when implementing a corrective action results in a cost savings. If the AFC is the same or greater than the EFC, the rank is *no change* (*NC*).

For Product X, there are 37 instances out of 63 potential opportunities where the corrective action results in a cost savings. Figure 5-7 shows the risk rank, where 1 is the highest risk, found by the EIV decision metric. The EIV decision metric only ranks risks where a corrective action is cost effective to implement. The gaps in the number line show the item numbers that are cost intensive and do not have a rank using the EIV decision metric. For the EI-FMEA method, there is a total CFC of $2,206,361.31 for Product X, which is a cost savings from the EFC of $4,073,222.28 (i.e., 65.2%) over the 10-year life cycle.

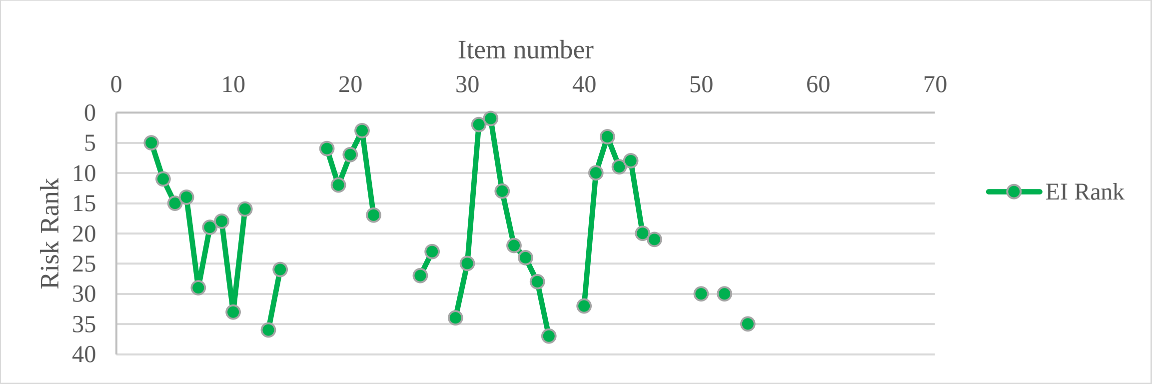


Figure 5-7. EI-FMEA failure mode item number versus risk rank.

5.4 FMEA Method Evaluation

Each of the three FMEA methods have unique risk prioritization metrics. Table A-1 summarizes all 63 failure modes, failure effects, root causes, RPN, RPN rank, EFC, EFC rank, EIV, and EIV rank. The three FMEA methods report differing risks for similar failure modes. The RPN results in 31 unique numbers, EFC results in 43 unique numbers, and EIV results in 58 unique numbers. Table 5-4 shows the top 10 failure mode item numbers found by each method.

Table 5-4. Risk Rank by Method

Risk Rank	**Item Number**		
	RPN	**EFC**	**EIV**
1	48	31	32
2	47	32	31
3	49	21	21
4	53	42	42
5	31	43	3
6	55	18	18
7	58	44	20
8	42	20	44
9	40	41	43
10	62	19	41

Comparing the RPN risk prioritization to the EIV risk prioritization (Figure 5-8), the methods rank risk in differing ways. The top three risks found using the RPN are not even ranked for change based on the EIV method. Looking at the failure modes, the high ratings from the RPN metric come from failures that occur during operation with limited detection methods. These same failures are shown as *no change* in the EIV risk prioritization method due to the low probability of failure paired with a cost-intensive corrective action.

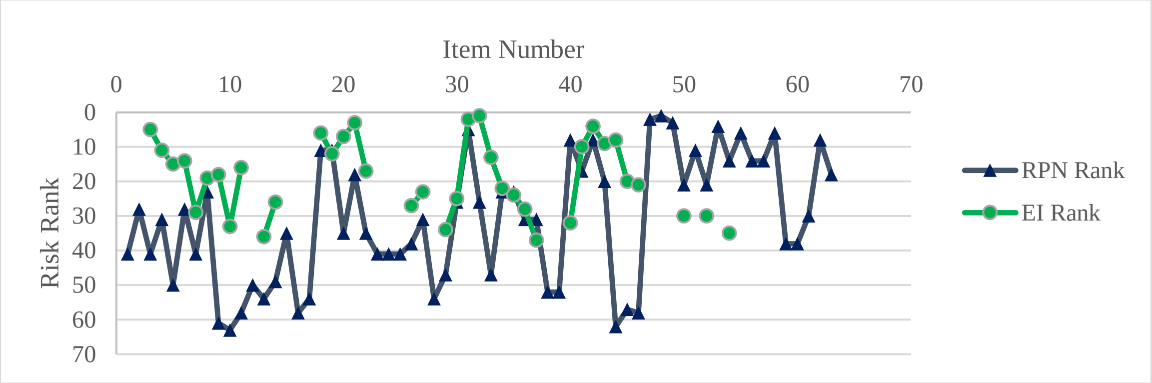


Figure 5-8. RPN versus EIV risk rankings by failure mode item number.

Similar RPN numbers do not result in similar EIV. As shown in Table 5-5, there is a large range between a single RPN value and the EIV. For example, items 3 and 24 have an RPN of 64, but there is an economic difference between them of approximately $789,000. Using the RPN metric, item number 3 would not be addressed and a savings of $275,449 would not be realized.

Table 5-5. Similar RPN Versus EIV Values

Item	RPN	RPN Rank	EIV ($)	EIV Rank
1	64	41	234,762.30	NC
3	64	41	(275,448.79)	5
7	64	41	(4,075.86)	29
23	64	41	1,632.00	NC
25	64	41	254,218.31	NC
24	64	41	513,227.06	NC
42	168	8	(498,040.88)	4
40	168	8	(3,316.80)	32
62	168	8	3,264.00	NC

The EFC risk prioritization metric and the EIV risk prioritization metric also produce differing results (Figure 5-9). The EIV rank is calculated after measuring the impact of implementing a corrective action. This allows the ranks to change based on larger potential savings through cost-reduction efforts that are not present during the ranking of the EFC. The EFC rank also needs to be evaluated further to determine if the corrective action is cost effective. A cost intensive corrective action can create gaps in the EFC risk rank scale where certain values are eliminated.

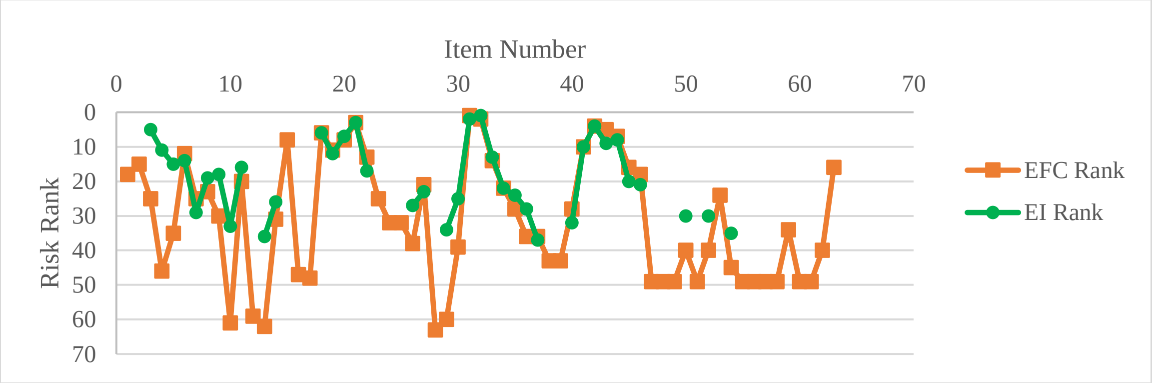


Figure 5-9. EFC versus EIV risk rankings by failure mode item number.

Like similar RPN numbers, similar EFC does not result in similar EIV. As shown in Table 5-6, there is a large range between a single EFC value and the EIV. For example, items 3 and 23 have an EFC of $17,256.04, but there is an economic difference between them of approximately $277,000.

Table 5-6. Similar EFC Versus EIV Values

Item	EFC	EFC Rank	EIV ($)	EIV Rank
3	$ 17,256.04	25	(275,448.79)	5
7	$ 17,256.04	25	(4,075.86)	29
23	$ 17,256.04	25	1,632.00	NC

For further comparison, each failure mode item number uses the economic impact value and is ordered based on its risk rank and corrective action implementation criteria from each FMEA method. LCB-FMEA and EI-FMEA can combine multiple outcomes to create a failure scenario where a failure scenario is the sum of individual failure effects given a single root cause. Figure 5-10 shows the cumulative cost savings through the implementation of corrective actions for RPN and EIV. There is a significant cost delta between the RPN and EIV risk prioritization metrics. The EIV method results in a total savings of $4,201,706.52 while the RPN method results in a total savings of $2,888,733.95 for a cost delta of $1,312,972.57 between the methods. There are 29 failure modes addressed by the RPN and 27 failure scenarios by the EIV.

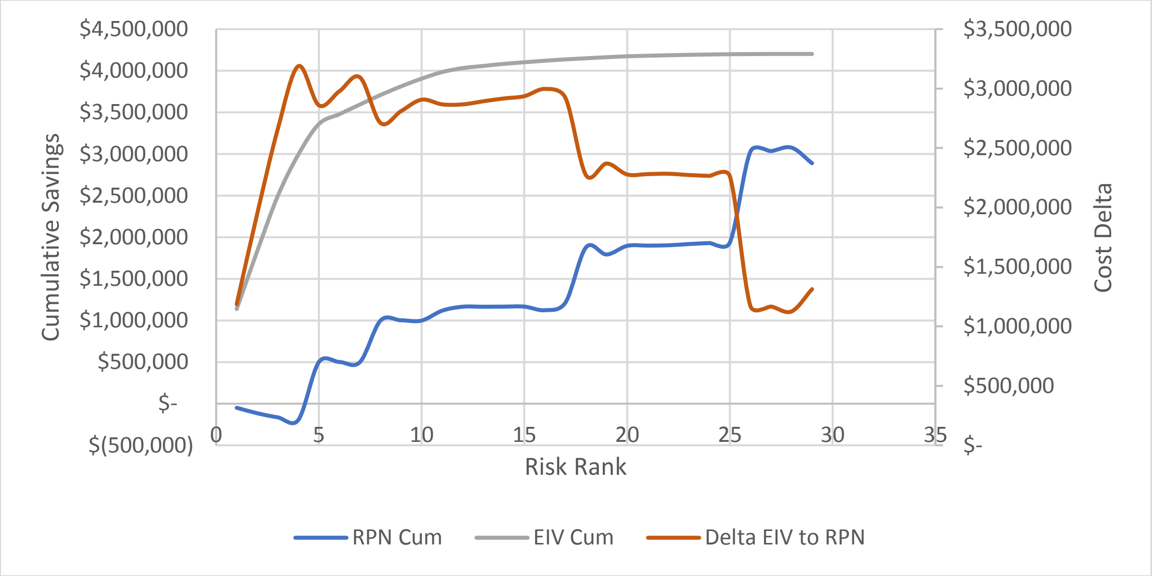


Figure 5-10. RPN versus EIV cumulative savings.

Both LCB-FMEA and EI-FMEA implement corrective actions based on cost effectiveness, but they differ in the way they rank risks. Figure 5-11 shows the difference in the cumulative cost savings for the two methods. They share the same total savings and the number of failure modes addressed, but they differ where the cost savings occur. If only the highest priority risk is implemented from each method, the EI-FMEA results in a savings of $1,137,425.16 while the LCB-FMEA results in a savings of $695,419.87. The savings delta between EI-FMEA and LCB-FMEA is between $260,000 and $360,000 from risk ranks 5 to 18. The savings delta can become significant when there are finite resources for corrective actions and only a certain number of corrective actions (e.g., the top 10 risk ranks) can be implemented.

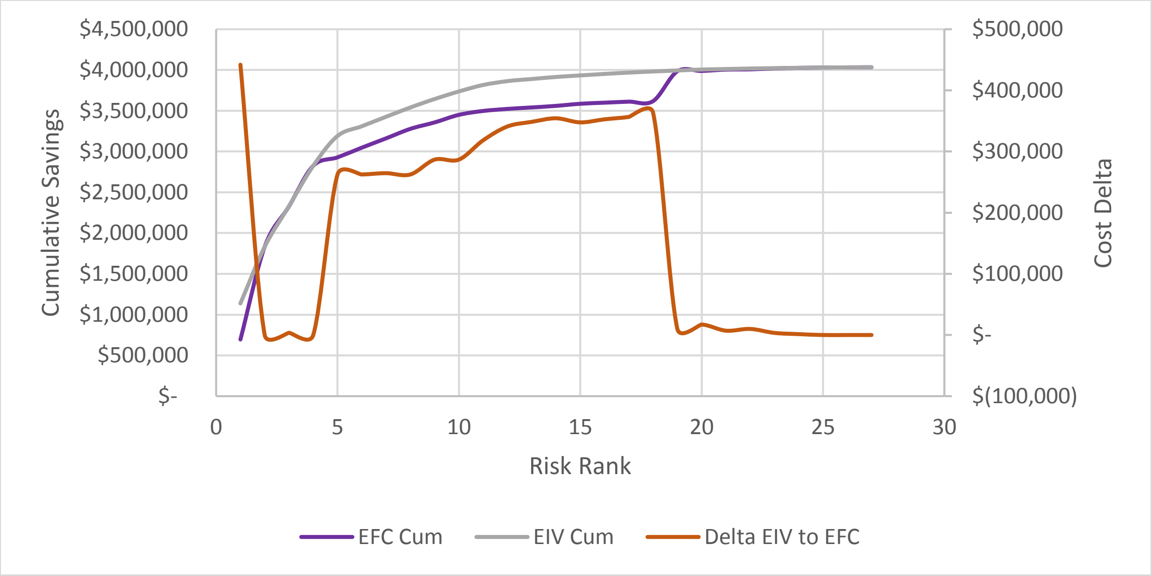


Figure 5-11. EFC versus EIV cumulative savings.

5.5 Summary

In this chapter, Product X—a CMC cover used in the aerospace industry—is introduced. Product X is currently transitioning from development to production. Three different FMEA methods (traditional FMEA, LCB-FMEA, and EI-FMEA) are preformed to identify potential failure modes in the process and design. The risk prioritization metrics are compared to determine how each FMEA method ranks risk based on estimated cost savings.

EI-FMEA showed a significant cost savings compared to traditional FMEA based on the implementation of the corrective actions found using the methods' risk prioritization metrics.

Both LCB-FMEA and EI-FMEA use cost effectiveness as the criteria for implementing a corrective action. Where LCB-FMEA ranks risk based on potential cost savings (i.e., EFC), EI-FMEA ranks risk based on estimated cost savings (i.e., EIV). The difference is EI-FMEA incorporates the implementation cost and effect into the rankings where LCB-FMEA does not. While both methods result in the same overall savings, EI-FMEA's risk prioritization can save more money when there are finite resources for implementing corrective actions.

CHAPTER VI

PRACTICAL APPLICATIONS FOR EI-FMEA

In this chapter, I discuss the practical applications of the EI-FMEA method, beginning with a theoretical example for a desktop computer. I evaluate the design of the computer to select the HDD and options that would lower the manufacturer's cost. Next, I perform a case study using Product X from Chapter V and examine the highest priority failure modes, based on the EI-FMEA risk prioritization metric, to implement corrective actions. I then determine the probability of failure over a number of units to compare the estimated probability of failure with the actual probability of failure. The chapter concludes with a summary of the practical uses of EI-FMEA.

6.1 Design EI-FMEA

Using the EI-FMEA method at an earlier stage results in larger potential benefits. During the initial product design, EI-FMEA can be used to select initial components, establish fabrication processes, determine product reliability, and check product conformance to a specification. The design phase accounts for the majority of the life cycle cost; by the end of the design phase, 75% of the life cycle cost has been committed to the product while only 15% of the actual life cycle cost has been spent (SAE International, 1992). Choosing the right components for a product early in the design phase is critical.

6.2 Computer System Example

A computer company, Lily Pad Computers (LPC), wants to design a new computer system called the LPC 712. The goal of the design is to have a computer system with multiple storage options for users. LPC's users typically use the computer for home cloud networks and expect the computer to have a large storage capacity for multimedia files. The computer system (Figure 6-1) includes a keyboard, mouse, monitor, speaker system, and a tower that houses the HDD that determines the system's storage capacity.

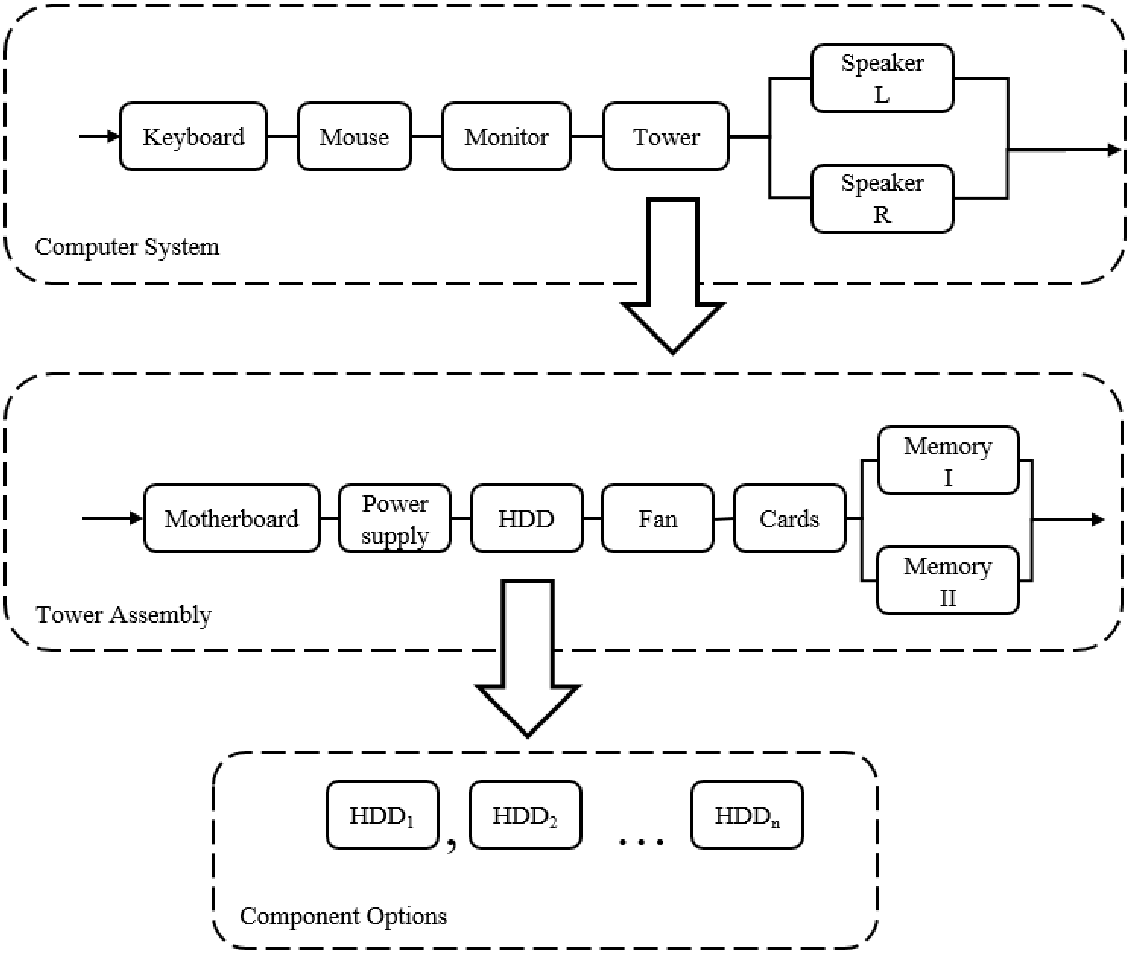


Figure 6-1. LPC computer block diagram.

LPC's system engineer has been tasked with selecting for the LPC 712 models a HDD with a 3 terabyte (TB) HDD, 4 TB HDD, and 8 TB HDD. There are four main manufacturers with multiple models of HDDs. The manufacturers are HGST, Seagate, Toshiba, and Western Digital Corporation (WDC). Once again, I use HDD data collected by Backblaze over a 4-year period to select the HDDs for the LPC 712-3, LPC 712-4, and LPC 712-8. The drive failure numbers shown in Table 6-1 have been recorded for varying models of HDD and storage capacity since 2013.

Table 6-1. HDD Failure Data from April 2013 Through March 2017

Item	Manufacturer	Model	Drive size (TB)	Drive count	Drive days	Drive failures
1	HGST	HUH728080ALE600	8	45	34,828	2
2	Seagate	ST8000DM002	8	8,660	1,891,214	71
3	Seagate	ST8000NM0055	8	60	39,119	2
4	HGST	HDS5C4040ALE630	4	75	271,674	4
5	HGST	HMS5C4040BLE640	4	9,362	5,224,341	93
6	HGST	HMS5C4040ALE640	4	7,085	6,714,263	114
7	Toshiba	MD04ABA400V	4	146	101,523	4
8	WDC	WD40EFRX	4	46	50,640	3
9	Seagate	ST4000DM000	4	34,737	25,915,163	2,077
10	HGST	HDS5C3030ALA630	3	4,595	6,317,882	144
11	HGST	HDS723030ALA640	3	1,027	1,397,042	73
12	Toshiba	DT01ACA300	3	58	68,426	7
13	Seagate	ST33000651AS	3	293	222,147	26
14	WDC	WD30EFRX	3	1,102	1,124,720	165
15	WDC	WD30EZRX	3	388	123,577	25
16	Seagate	ST3000DM001	3	4,247	2,205,148	1,614
			Total	71,926	51,701,707	4,424

Note. Adapted from (Klein, 2017a, 2017b).

The baseline HDD can be chosen by selecting the HDD with the lowest EFC based on the drive size. To calculate the EFC, the probability of failure is found for each HDD by first finding the failure rate using Equation 4-6 and then converting the failure rate to the probability of failure for 1 year using Equation 4-8. The failure probabilities for each HDD are shown in Table 6-2.

Table 6-2. HDD Probability of Failure

Item	**Manufacturer**	**Model**	**Drive size (TB)**	**λ (annual)**	**Probability of failure (1 year)**
1	HGST	HUH728080ALE600	8	0.0210	0.0207
2	Seagate	ST8000DM002	8	0.0137	0.0136
3	Seagate	ST8000NM0055	8	0.0187	0.0185
4	HGST	HDS5C4040ALE630	4	0.0054	0.0054
5	HGST	HMS5C4040BLE640	4	0.0065	0.0065
6	HGST	HMS5C4040ALE640	4	0.0062	0.0062
7	Toshiba	MD04ABA400V	4	0.0144	0.0143
8	WDC	WD40EFRX	4	0.0216	0.0214
9	Seagate	ST4000DM000	4	0.0293	0.0288
10	HGST	HDS5C3030ALA630	3	0.0083	0.0083
11	HGST	HDS723030ALA640	3	0.0191	0.0189
12	Toshiba	DT01ACA300	3	0.0373	0.0367
13	Seagate	ST33000651AS	3	0.0427	0.0418
14	WDC	WD30EFRX	3	0.0535	0.0521
15	WDC	WD30EZRX	3	0.0738	0.0712
16	Seagate	ST3000DM001	3	0.2672	0.2344

Next, the system engineer calculates the EFC for each HDD. The HDDs all experience the same potential failure modes and repair times, so, for simplicity, the system engineer calculates the cost to repair/replace a failed HDD. LPC has a standard warranty period of 1 year and a yearly production quantity of 500,000 for each model; therefore, the EFC is calculated for a single year of production. From Equation 3-8, the EFC is found:

$$EFC\ of\ HDD\ 1 = C_i * p_i * q_j = 269.99 * .0207 * (500{,}000 * 1) = \$2{,}800{,}067.62$$

The baseline HDDs are chosen for the LPC 712-3, LPC 712-4, and LPC 712-8 based on the lowest EFC, which is shown in Table 6-3.

Table 6-3. EFC of HDD by Size

Item	Manufacturer	Model	Cost of drive ($)	Drive size (TB)	Annual quantity	Probability of failure (1 year)	Expected failure cost ($)	EFC Rank (by drive size)
1	HGST	HUH728080ALE600	269.99	8	500,000	0.0207	2,800,067.62	3
2	Seagate	ST8000DM002	259.00	8	500,000	0.0136	1,762,414.96	1
3	Seagate	ST8000NM0055	264.99	8	500,000	0.0185	2,449,563.60	2
4	HGST	HDS5C4040ALE630	126.92	4	500,000	0.0054	340,124.88	1
5	HGST	HMS5C4040BLE640	113.99	4	500,000	0.0065	369,122.83	2
6	HGST	HMS5C4040ALE640	119.95	4	500,000	0.0062	370,531.05	3
7	Toshiba	MD04ABA400V	129.99	4	500,000	0.0143	928,002.86	4
8	WDC	WD40EFRX	134.20	4	500,000	0.0214	1,435,343.94	5
9	Seagate	ST4000DM000	107.94	4	500,000	0.0288	1,555,933.52	6
10	HGST	HDS5C3030ALA630	87.00	3	500,000	0.0083	360,385.95	1
11	HGST	HDS723030ALA640	67.99	3	500,000	0.0189	642,223.75	2
12	Toshiba	DT01ACA300	82.46	3	500,000	0.0367	1,511,124.07	3
13	Seagate	ST33000651AS	84.99	3	500,000	0.0418	1,777,134.11	4
14	WDC	WD30EFRX	109.95	3	500,000	0.0521	2,866,302.37	5
15	WDC	WD30EZRX	123.76	3	500,000	0.0712	4,404,634.82	6
16	Seagate	ST3000DM001	73.98	3	500,000	0.2344	8,672,061.61	7

The baseline HDDs are summarized in Table 6-4.

Table 6-4. LPC 712 Baseline HDD

Manufacturer	Model	Drive size (TB)	Expected failure cost ($)	EFC Rank by drive size
Seagate	ST8000DM002	8	1,762,414.96	1
HGST	HDS5C4040ALE630	4	340,124.88	1
HGST	HDS5C3030ALA630	3	360,385.95	1

The cost of each computer model (LPC 712-3, LPC 712-4, and LPC 712-8) is the same based on HDD size regardless of the cost of the HDD. LPC requires the HDD to have a probability of failure no greater than 0.10 after a 5-year period. The next step is to calculate the AFC and EIV for each HDD model in comparison to the baseline HDD. This allows for the cost of the HDD and 5-year probability of failure requirement to be evaluated to minimize the failure cost for the LPC 712 computer system. The probability of failure in 5 years is found by using the annual failure rate of each model in Equation 4-8. Two of the 4-TB HDDs and five of the 3-TB HDDs are eliminated (see Table 6-5) because their 5-year probability of failure exceeds 0.10.

Table 6-5. HDD Probability of Failure in 5 Years

Item	Manufacturer	Model	Drive size (TB)	λ (annual)	Probability of failure (5 year)
1	Seagate	ST8000DM002	8	0.0137	0.0662
2	Seagate	ST8000NM0055	8	0.0187	0.0891
3	HGST	HUH728080ALE600	8	0.0210	0.0995
4	Seagate	ST4000DM000	4	0.0293	**0.1361**
5	HGST	HMS5C4040BLE640	4	0.0065	0.0320
6	HGST	HMS5C4040ALE640	4	0.0062	0.0305
7	HGST	HDS5C4040ALE630	4	0.0054	0.0265
8	Toshiba	MD04ABA400V	4	0.0144	0.0694
9	WDC	WD40EFRX	4	0.0216	**0.1025**
10	HGST	HDS723030ALA640	3	0.0191	0.0910
11	Seagate	ST3000DM001	3	0.2672	**0.7370**
12	Toshiba	DT01ACA300	3	0.0373	**0.1703**
13	Seagate	ST33000651AS	3	0.0427	**0.1923**
14	HGST	HDS5C3030ALA630	3	0.0083	0.0407
15	WDC	WD30EFRX	3	0.0535	**0.2349**
16	WDC	WD30EZRX	3	0.0738	**0.3087**

The baseline HDDs for each computer model (Table 6-4) become the initial failure input in the EI-FMEA method. The corrective action becomes replacing the baseline HDD with another HDD option per the drive size. The AFC (Equation 3-10), EIV (Equation 3-11), and EIV rank are calculated to determine which HDD should be selected for each LPC 712 model. For the LPC 712-8, the baseline HDD (Seagate ST8000DM002) results in the best option. For the LPC 712-4, two HDD options show more cost savings than the baseline HDD (HGST HDS5C4040ALE630). The HDD with the highest EIV rank is the HGST HMS5C4040BLE640, which gives a cost savings of $6,436,002.05. For the LPC 712-3, the HDD with the highest EIV rank is the HGST HDS723030ALA640 with a cost savings of $9,223,162.20 over the baseline HDD (HGST HDS5C3030ALA630). The total savings from using the EI-FMEA method during the LPC 712 design is $15,659,164.25.

Table 6-6. EI-FMEA LPC 712 HDD Rank

Item	**Manufacturer**	**Model**	**Cost of drive ($)**	**EFC Rank**	**Recurring implementation cost ($)**	**Adjusted failure cost ($)**	**EIV ($)**	**EIV Rank**	**Corrected failure cost ($)**	**Savings ($)**
1	**Seagate**	**ST8000DM002**	**259.00**	**1**	**0.00**	**1,762,414.96**	**0.00**	**NC**	**1,762,414.96**	**0.00**
2	Seagate	ST8000NM0055	264.99	2	5.99	5,444,563.60	3,682,148.64	NC	1,762,414.96	0.00
3	HGST	HUH728080ALE600	269.99	3	10.99	8,295,067.62	6,532,652.66	NC	1,762,414.96	0.00
5	**HGST**	**HMS5C4040BLE640**	**113.99**	**2**	**(12.93)**	**(6,095,877.17)**	**(6,436,002.05)**	**1**	**(6,095,877.17)**	**(6,436,002.05)**
6	HGST	HMS5C4040ALE640	119.95	3	(6.97)	(3,114,468.95)	(3,454,593.83)	2	(3,114,468.95)	(3,454,593.83)
7	HGST	HDS5C4040ALE630	126.92	1	0.00	340,124.88	0.00	NC	340,124.88	0.00
8	Toshiba	MD04ABA400V	129.99	4	3.07	2,463,002.86	2,122,877.98	NC	340,124.88	0.00
10	**HGST**	**HDS723030ALA640**	**67.99**	**2**	**(19.01)**	**(8,862,776.25)**	**(9,223,162.20)**	**1**	**(8,862,776.25)**	**(9,223,162.20)**
14	HGST	HDS5C3030ALA630	87.00	1	0.00	360,385.95	0.00	NC	360,385.95	0.00
									Total	**(15,659,164.25)**

The EI-FMEA allows users to compare the initial cost of the HDD in the ranking calculation. Since the cost of the computer system is the same regardless of the cost of the HDD, there is a cost savings in selecting a cheaper HDD with a higher probability of failure for both the LPC 712-3 and LPC 712-4 models. For the LPC 712-8, the lowest-cost HDD also has the lowest probability of failure. The higher probability of failure is acceptable to LPC based on the 0.10 probability of failure requirement over 5 years. Using the EI-FMEA method results in significant savings to LPC compared to using the EFC rank as a design metric.

6.3 Product X Case Study

In Chapter V, Product X is introduced as a CMC cover used in the aerospace industry. I perform an EI-FMEA on Product X to help identify failure modes and rank potential corrective actions as Product X transitioned to production. A case study is being performed on Product X using the results of the EI-FMEA found in section 5.3.3 to measure the impact of the EI-FMEA method on Product X. The EIV risk prioritization metric has identified 27 corrective actions that should be implemented to reduce the failure cost of Product X at an implementation cost of ~$174,000.

6.3.1 Corrective Action Implementation

Due to finite resources, not all of the corrective actions can be implemented simultaneously. The first barrier is the overall cost to implement. To implement a corrective action, management approval is needed to allocate the necessary funds. The second complication is a resource bottleneck where multiple items require the same resource, such as a tooling design engineer, for implementation. For Product X, management approval is given to pursue the top three risks based on EIV value (shown in Table 6-7). The estimated time to implement the top three items is 2 months, during which time Product X production will be on hold.

Table 6-7. Product X Top Risks Ranked by EI

Item/Function	Potential Failure Mode	Potential Root Cause of Failure	Potential Effects of Failure	Improvement Plan / Corrective Action	Cost to Implement ($)	EIV ($)	Rank
Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Robot sprayed uneven interior coating	Fails leak test – scrap	New robot	18,160.00	(1,137,425.16)	1
Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Interior surface not clean prior to application of interior paint	Fails leak test – scrap	Addition of ultrasonic clean procedure	13,616.00	(695,419.87)	2
Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Large internal stress in assembly	Fails burst pressure test – scrap	Match frame to CMC cover based on thermal expansion	50,800.00	(662,607.26)	3

6.3.2 Results and Conclusions

During the 2-month hold on production, the new cleaning procedure was the first corrective action to be implemented. It involved finding an outside supplier with expertise in ultrasonic cleaning. The cleaning parameters were developed with the cleaning supplier and the process engineer for Product X. The new paint coating machine was also purchased and brought online. A study was carried out to reduce stress in the assembly by matching the CMC cover to the frame based on the coefficient of thermal expansion (CTE) of each component. A system was developed for measuring the CTE of the frame to determine which CMC cover should be used in the bonded assembly. Four initial units went through the CTE matching, new cleaning procedure, and new coating machine. The first two parts passed the leak rate requirement but failed during the burst pressure test requirement. The next two parts were given the burst test prior to the cleaning procedure and the new coating machine. There was a concern that the ultrasonic cleaning method could be damaging the part. One of the parts passed the burst pressure test, but the second part failed. The part that passed the burst pressure test went through the clean procedure and new coating machine and passed the leak rate requirement. This led the engineering team to determine the CTE matching method was not reducing the internal stress of the assembly, so an in-depth investigation was performed.

Table 6-8. Development Test Results

Serial number	Ultrasonic clean	New coat machine	CTE match method	Leak rate test	Burst pressure test
4001	Yes	Yes	Yes	Pass	Fail
4002	Yes	Yes	Yes	Pass	Fail
4003	Yes	Yes	Yes	Pass	Pass
4004	No	No	Yes	N/A	Fail

The failure investigation on the burst pressure test for Product X resulted in a significant effort to determine the root cause of the failures. The cure cycle was found to be the underlying root cause for the burst pressure test failures. A new cure cycle was developed and tested on two units to their ultimate pressure load to determine the pressure load margin. The test to ultimate load was required for implementing the new cure profile. The implementation cost also increased due to the investigation. Table 6-9 compares the actual implementation costs against the estimated implementation cost for each of the three failure modes.

Table 6-9. Actual and Estimated Implementation Costs

Item	EFC ($)	Estimated implementation cost ($)	Actual implementation cost ($)	Estimated EIV ($)	Updated EIV ($)
1	1,232,307.43	18,160.00	28,264.00	(1,137,425.16)	(1,127,321.16)
2	2,365,384.62	13,616.00	8,160.00	(695,419.87)	(700,875.87)
3	739,285.71	50,800.00	214,000.00	(662,607.26)	(499,407.26)

Since the implementation of the new cure profile, ultrasonic cleaning procedure, and new coating machine, there have been 42 assemblies of Product X with no failures. The expected failure cost using the probability of failure before the corrective action implementation and after the corrective action implementation for the 42 assemblies is shown in Table 6-10. EI-FMEA method provides the economic impact over the life cycle of a product. As the product matures, updating the failure cost based on the build data helps to make comparisons to the estimated probability of failure and repair times. The EI-FMEA is a living method and should be performed anytime there is a major change to the system.

Table 6-10. Failure Cost Analysis

Item	Quantity	P_f before CA	P_f after CA	Failure cost ($)	Estimated failure cost before CA ($)	Estimated failure cost after CA ($)	Actual failure cost after CA ($)
1	42	0.1099	0.00667	7,175	33,118	2,010	0
2	42	0.2198	0.00154	7,175	66,237	4,664	4,200
3	42	0.0659	0.00231	7,475	20,689	725	0

The probability of manufacturing 42 passing parts in a row can be found by taking the original probability of success (i.e., 1 - probability of failure) to the 42nd power, assuming the failures are independent. Table 6-11 shows the probability of 42 parts passing in a row both before the CA was implemented and after the CA was implemented.

Table 6-11. Probability of Success for 42 Parts in a Row

Item	Probability of failure before CA	Probability of failure after CA	Probability of 42 pass before CA	Probability of 42 pass after CA
1	0.1099	0.00667	0.0075	0.7551
2	0.2198	0.00154	0.00003	0.9374
3	0.0659	0.00231	0.0570	0.9075

6.4 Summary

The computer design example and Product X case study show two practical applications for the EI-FMEA. As discussed in section 2.2.2, FMEA is used in a wide variety of industries for a wide variety of practical applications. The addition of the costing element and EIV risk prioritization metric used in the EI-FMEA method allows for new product designs to be based on minimizing the expected failure cost. The case study on Product X shows that EI-FMEA is a living method; reviewing and updating the results helps the product to become more mature.

CHAPTER VII

CONCLUSION

In this chapter, I discuss a summary of the research, recommendations for future work, and this study's contributions to the body of knowledge.

7.1 Summary of the Research

7.1.1 Problem Overview

In today's marketplace, companies face competition on a global scale. To be competitive, a company needs a high-quality part, low product-development times, and low failure costs (Carlson, 2012). Dependability analysis techniques are available to companies to help meet these demands. One dependability analysis technique widely used in manufacturing is FMEA, but there are multiple documented limitations to the FMEA method including ambiguity of the risk prioritization metric (H.-C. Liu et al., 2013). FMEA uses the RPN as a risk prioritization metric and for the allocation of finite resources for corrective action. The ambiguity of the RPN risk prioritization metric in FMEA, however, produces inconsistent risk prioritization (L.-Y. Chen & Yeh, 2014; Gargama & Chaturvedi, 2011; Kmenta & Ishii, 2005). The cost associated to improve the system quality (i.e., allow the system to meet a specification) can be between 20%–50% of sales, thus reducing a company's ability to be competitive in the marketplace (Dahlgaard & Dahlgaard, 2002; Gupta & Campbell, 1995; Sandoval-Chávez & Beruvides, 1998). Any new risk prioritization method needs to have a decision-support system to determine when to implement a corrective action or improvement (H.-C. Liu et al., 2016).

7.1.2 Research Purpose

The purpose of this research is to develop an economic-impact-based failure mode and effects analysis that uses an economic-risk prioritization metric to prioritize risk and determine resource allocation in a manufacturing environment. Through this research, the following questions are answered:

1. *How can risk be prioritized to reduce failure cost?*
2. *How are finite resources allocated to reduce failure cost?*

7.1.3 Methodology Review

The first part of the research is the development of the economic-impact-based failure mode and effects analysis method. The method is derived from the current body of knowledge. The research community has named the ambiguity of the RPN and SOD variables as a major limitation to the traditional FMEA method (H.-C. Liu et al., 2013). Replacing the RPN and SOD variables in the traditional FMEA method addresses the limitation. The first reference to a cost-based risk evaluation criteria comes from Gilchrist (1993). He proposed replacing the SOD variables with a new set of variables including the probability of a failure occurring, the probability the customer receives the product, the cost of a failure event, and the quantity of products built. The product of the variables, which makes up the risk prioritization, is known as the failure cost. The method is further developed by Kmenta (2001), who includes failure scenarios and updates the variables to create the TEC, and Rhee (2005) who creates a detailed failure cost calculation and life cycle cost variable.

The EI-FMEA method uses cost-based methods as the foundation while creating a new set of variables for the risk prioritization and decision-support system. Continued analysis beyond the initial failure is one of the strengths of traditional FMEA that has not been implemented in previous cost-based methods. The resulting decision-support system uses the EIV risk prioritization metric to determine if a corrective action should be implemented after ranking risks by the largest reduction in failure cost. This allows for the user to base corrective action implementation on the potential economic value added over the life cycle of the program and provides a way to make decisions when there are finite resources.

This research validates the EI-FMEA method through the evaluation of multiple FMEA methods, the theoretical design of a new product, and a case study. An aerospace product, Product X, which is currently being transitioned from development to production, is used to evaluate three FMEA methods and their ability to rank risk while reducing failure cost. The three methods include traditional FMEA, which uses the RPN risk prioritization metric; LCB-FMEA, which uses the EFC risk prioritization metric; and EI-FMEA, which uses the EIV risk prioritization metric. A set of 63 individual failure modes are identified for Product X. Then, the risk prioritization metrics for each of the three FMEA methods are used to determine corrective action implementation. The results of the FMEA methods are shown based on the expected failure cost reduction through decision-support criteria using the risk prioritization metric.

The design for a theoretical product, the LPC 712 computer system, uses the EI-FMEA method to compare design alternatives and to find ways to reduce failure rates and overall cost through component selection. For the LPC 712 example, I use a failure database, collected by Backblaze for HDD on their cloud storage center, for selecting HDD options for the LPC 712 based on storage size. The initial HDD for each model is chosen based on EFC and then compared to the reliability requirements. Finally, I use the EI-FMEA decision-support system for selecting the HDD with the lowest estimated failure cost over the LPC 712 life cycle.

The final validation uses a case study on Product X where the top three failures identified during the FMEA evaluation by the EI-FMEA method are implemented and the results presented.

7.1.4 Major Findings

7.1.4.1 FMEA Evaluation

Each of the three FMEA methods has differing results when ranking the failure modes. The decision-support system for traditional FMEA is determined by the FMEA team, so I choose any RPN over 100 as the criteria to implement a corrective action. For LCB-FMEA, the decision-support system is not well defined and only recommends implementing a corrective action if the action is economically sustainable. LCB-FMEA does not include the decision-support criteria in the risk prioritization ranking, which leads to confusion in the risk rank. A high-value risk rank may not lead to a corrective action being implemented due to high implementation cost. The EI-FMEA method incorporates the decision-support criteria into the risk prioritization metric. Like the LCB-FMEA method, only corrective actions that are economically sustainable are implemented in EI-FMEA, but, unlike the LCB-FMEA method, the EIV risk prioritization rank has already incorporated this value. Figure 7-1 shows the cumulative failure cost reduction for each FMEA method when only looking at the risk prioritization rank. Both traditional FMEA and EI-FMEA can use their decision-support criteria along with the risk rank for corrective action implementation. For LCB-FMEA, decision-support criteria cannot be determined based on the EFC or risk rank, making it difficult to know which corrective actions should be implemented.

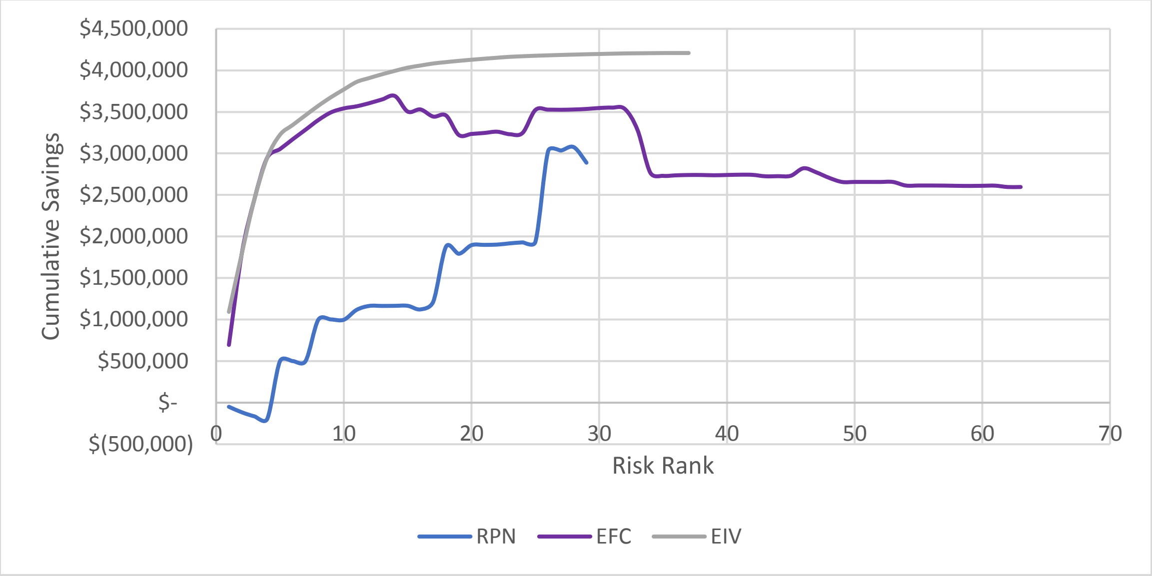


Figure 7-1. Cumulative failure cost reduction versus risk rank.

Another finding during the FMEA evaluation is the relationship between similar RPN values and EIV as well as between similar EFC values and EIV. For example, in Table 5-5, a failure mode with RPN value of 64 could have a difference in EIV of approximately $789,000. Likewise, Table 5-6 shows failure modes with similar EFC values having a difference in EIV of approximately $277,000.

7.1.4.2 EI-FMEA Product Design

The LPC 712 computer system's design uses the EI-FMEA method to compare design decisions in relation to the HDD to use for the different computer system models. The baseline HDD is chosen using the EFC, which selects the HDD based on the highest reliability. The EI-FMEA allows for a comparison of design alternatives to the baseline HDD, taking into account the HDD's system reliability requirements and initial cost. In Table 6-6 the full outcome of the design alternative using the EI-FMEA results in a failure cost reduction of over $15.6 million. The EI-FMEA method allows the comparison of design alternatives that can sacrifice some performance for a cost savings while still meeting requirements. Including the recurring cost calculation in the EI-FMEA method makes this possible.

7.1.4.3 Product X Case Study

The case study on Product X shows how the EI-FMEA method can be used when there are finite resources. For this case study, only the top three failure modes identified by the EIV recommended implementing corrective action. This is due to a limit on funds available to implement corrective actions. During the implementation of the corrective actions in the case study, one of the corrective actions increases the probability of failure, and the product line is shut down for an extended time for a failure investigation until implementing a new corrective action. With the new corrective action implemented and the product line back in production, 42 units are fabricated and tested with no failures. Table 6-11 shows a low probability of the success of the passing parts due to chance alone.

7.2 Recommendations for Future Work

7.2.1 External Failure Cost

The EI-FMEA focuses on visible external failure cost over non-visible external failure cost. The incorporation of the external failure cost can be used for calculating visible external failure cost, but does not have a detailed procedure for establishing non-visible external failure cost. As I discussed in section 2.1.2, external failure cost is difficult to estimate as the true cost of a defective product reaching the customer may not be known for years. A detailed external failure cost should include both visible (e.g., warranty claims, product returns, product repair times) and non-visible (e.g., loss of customers, reduced perceived quality) costs. A detailed external failure cost calculation can help to improve the EI-FMEA by taking into account the non-visible failure cost and impact of a defective product reaching the customer.

7.2.2 Best Method for Reducing Failure Cost

In chapter V, EI-FMEA was compared to traditional FMEA and LCB-FMEA. The results show each method ranking risk in a different way that results in differing failure cost reductions. Further research could evaluate the three methods based on the largest failure cost reduction over multiple studies to determine if one of the methods consistently produces the lowest failure cost. This would contribute to the body of knowledge by showing which method is the best way to reduce failure cost through preventative and corrective action.

7.2.3 Time to Perform

The time to perform an FMEA has been listed as a limitation to the method by multiple researchers (Bluvband & Grabov, 2009; Carmignani, 2009; Goble, 2012; Kmenta, 2001; Price & Taylor, 2002). The EI-FMEA method has more steps and calculations than traditional FMEA and LCB-FMEA. One of the limitations of EI-FMEA discovered during the research is the time needed to complete a product evaluation. Future research could focus on reducing the amount of time needed to make an input and look to reduce or streamline the amount of manual calculations. Making the EI-FMEA less time consuming would contribute to the body of knowledge by addressing the time to perform limitation.

7.3 Contributions to the Body of Knowledge

There are multiple gaps in the literature with respect to FMEA. The EI-FMEA addresses the ambiguity of the SOD variables and RPN risk prioritization decision metric of traditional FMEA by replacing them with the probability of failure, the failure cost, and the EIV risk prioritization decision metric. This research also allows for the comparison of one study to another study and for a quantifiable measure of improvement by using cost as the decision metric.

Current cost-based FMEA methods and their respective risk prioritization decision metrics do not define an economic factor for corrective action implementation. The EIV risk prioritization metric has a decision-support system to determine when to implement a corrective action and to rank only improvements that are economically sustainable; H.-C. Liu et al. (2016) list these abilities as requirements for a new risk prioritization method.

7.4 Final Remarks

The EI-FMEA is a new dependability analysis that is created to determine failure modes, calculate failure cost, calculate corrective action implementation cost, and rank risk based on the largest potential reduction in failure cost. Having this tool allows companies to create high-quality parts, lower product development times, and reduce failure costs to be competitive in a global environment.

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APPENDIX A

Table A-1. Chapter V FMEA Summary

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
1	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during shipping	Assembly fails burst pressure test - Part scrap	Manufacture	Mfg Inspect	64	41	1	66,263.07	11	422,201.43	NC
2	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during shipping	CMC cover fails incoming inspection -scrap	Manufacture	Mfg Inspect	105	28					
3	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during light table inspection	Assembly fails burst pressure test - Scrap	Manufacture	Mfg Inspect	64	41	2	22,911.86	23	(365,997.11)	5
4	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during light table inspection	CMC cover fails light table inspection -scrap	Manufacture	Mfg Inspect	84	31					
5	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during application of exterior paint	Assembly fails burst pressure test	Manufacture	Mfg Inspect	48	50	3	99,491.82	9	(79,172.82)	11
6	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during application of exterior paint	CMC cover scrapped due to damage	Manufacture	Mfg Inspect	105	28					

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
7	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during transfer to oven	Assembly fails burst pressure test - scrap	Manufacture	Mfg Inspect	64	41	4	36,123.94	15	(19,166.91)	15
8	CMC cover is free of defects	CMC cover is chipped	CMC cover is damaged during transfer to oven	CMC cover scrapped due to damage	Manufacture	Mfg Inspect	112	23					
9	Part number and serial number are legible on surface of CMC cover	Part number and/or serial number are not legible	Ink induction time to long	Symbolization rework	Manufacture	Mfg Inspect	21	61	5	17,307.69	26	(16,414.59)	17
10	Part number and serial number are legible on surface of CMC cover	Part number and/or serial number are not legible	Ink induction time to short	Symbolization rework	Manufacture	Mfg Inspect	15	63	6	2,420.25	40	(1,527.15)	26
11	Part number and serial number are legible on surface of CMC cover	Part number and/or serial number are not legible	Silk screen moved during application	Symbolization rework	Manufacture	Mfg Inspect	24	58	7	28,846.15	18	(25,813.90)	13
12	Frame is bonded to CMC cover	Frame does not bond to cover	Frame not dry	Assembly fails burst pressure test - scrap	Manufacture	Mfg Inspect	48	50	8	5,623.70	38	778.24	NC
13	Frame is bonded to CMC cover	Frame does not bond to cover	Frame not dry	Assembly fails leak test - rework	Manufacture	Mfg Inspect	36	54					

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14	Frame is bonded to CMC cover	Frame dimension out of tolerance	Incorrect machine profile used	Assembly fails leak test - scrap	Manufacture	Mfg Inspect	56	49	9	35,079.53	16	14,925.60	NC
15	Frame is bonded to CMC cover	Frame dimension out of tolerance	Incorrect machine profile used	Assembly fails burst pressure test - scrap	Manufacture	Mfg Inspect	80	35					
16	Frame is bonded to CMC cover	Frame dimension out of tolerance	Incorrect machine profile used	CMC cover does not fit in frame- frame scrap	Manufacture	Mfg Inspect	24	58					
17	Frame is bonded to CMC cover	Frame dimension out of tolerance	Incorrect machine profile used	Fails dimensional inspection - scrap	Manufacture	Mfg Inspect	36	54					
18	Cover assembly dimensional requirement	X does not meet dimensional requirement	Improper assembly jig setup	Scrap at dimensional inspection	Manufacture	Mfg Inspect	150	11	10	130,631.87	6	(118,731.82)	6
19	Cover assembly dimensional requirement	X does not meet dimensional requirement	Bond weight not correct during cure	Scrap at dimensional inspection	Manufacture	Mfg Inspect	150	11	11	54,801.38	12	(47,577.35)	12
20	Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Incorrect cure profile used	Fails burst pressure test - scrap	Manufacture	Mfg Inspect	80	35	12	123,214.29	8	(116,402.11)	7
21	Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Large internal stress in assembly	Fails burst pressure test - scrap	Manufacture	Mfg Inspect	128	18	13	739,285.71	3	(662,607.26)	3
22	Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Adhesive applied in wrong location	Fails burst pressure test - scrap	Manufacture	Mfg Inspect	80	35	14	51,689.63	13	(24,995.18)	14

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23	Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Adhesive is out of date	Fails burst pressure test - scrap	Manufacture	Mfg Inspect	64	41	15	17,256.04	27	1,632.00	NC
24	Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Internal defect in CMC raw cover	Fails burst pressure test - scrap	Manufacture	Mfg Inspect	64	41	16	12,950.44	33	513,227.06	NC
25	Cover assembly can hold pressure value at maximum required leak rate	X does not hold burst pressure	Internal defect in frame	Fails burst pressure test - scrap	Manufacture	Mfg Inspect	64	41	17	12,950.44	33	254,218.31	NC
26	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Wrong O-ring installed	Fails leak test - rework	Manufacture	Mfg Inspect	72	38	18	6,263.74	37	(4,789.96)	23
27	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Surface roughness of O-ring does not allow seal	Fails leak test - rework	Manufacture	Mfg Inspect	84	31	19	15,824.18	32	(11,312.18)	20
28	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Surface roughness of frame does not allow seal	Fails leak test - rework	Design	PT Test	36	54	20	536.61	41	16,213.05	NC
29	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Dressing not applied to O-ring prior to install	Fails leak test - rework	Manufacture	Mfg Inspect	60	47	21	2,554.95	39	(1,524.12)	27
30	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	O-ring not correctly placed in O-ring groove	Fails leak test - rework	Manufacture	Mfg Inspect	108	26	22	10,549.45	35	(6,177.61)	22

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
31	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Interior surface not clean prior to application of interior paint	Fails leak test - scrap	Manufacture	Mfg Inspect	189	5	23	2,365,384.62	1	(695,419.87)	2
32	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Operator sprayed uneven interior coating	Fails leak test - scrap	Manufacture	Mfg Inspect	108	26	24	1,232,307.43	2	(1,137,425.16)	1
33	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Operator sprayed uneven interior coating	Fails interior paint thickness - scrap	Manufacture	Mfg Inspect	60	47					
34	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Interior paint gun not setup properly	Fails leak test - scrap	Manufacture	Mfg Inspect	112	23	25	41,403.34	14	(18,255.15)	16
35	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Interior paint gun not setup properly	Fails interior paint thickness - scrap	Manufacture	Mfg Inspect	112	23					

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
36	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Clog in interior paint gun	Fails leak test - scrap	Manufacture	Mfg Inspect	84	31	26	19,889.10	25	(4,199.33)	24
37	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Clog in interior paint gun	Fails interior paint thickness - scrap	Manufacture	Mfg Inspect	84	31					
38	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	O-ring leak on needle of paint gun	Fails leak test - scrap	Manufacture	Mfg Inspect	42	52	27	16,574.25	28	19,004.63	NC
39	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	O-ring leak on needle of paint gun	Fails interior paint thickness - scrap	Manufacture	Mfg Inspect	42	52					
40	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Interior paint not mixed correctly	Fails leak test - scrap	Manufacture	Mfg Inspect	168	8	28	16,563.49	29	(3,316.80)	25

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
41	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	Interior paint not properly cured	Fails leak test - scrap	Manufacture	Mfg Inspect	140	17	29	99,445.50	10	(92,841.23)	10
42	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	CMC cover damaged during installation on seal test fixture	Fails leak test - scrap	Manufacture	Mfg Inspect	168	8	30	583,125.00	4	(498,040.88)	4
43	Cover assembly can hold pressure value at maximum required leak rate	X does not meet maximum leak rate	CMC cover damaged during installation on test apparatus	Fails leak test - scrap	Manufacture	Mfg Inspect	126	20	31	140,156.25	5	(103,475.90)	9
44	Product X installs to next higher assembly	Fasteners do not thread into frame	Threads damaged during seal test	X cannot be installed - rework	Manufacture	Mfg Inspect	20	62	32	128,159.34	7	(114,281.15)	8
45	Product X installs to next higher assembly	Fasteners do not thread into frame	Threads damaged during installation	X cannot be installed - rework	Installation	PD Inspect	32	57	33	27,436.35	19	(13,298.29)	18
46	Product X installs to next higher assembly	Fasteners do not thread into frame	Threads damaged during burst pressure test	X cannot be installed - rework	Manufacture	Mfg Inspect	24	58	34	25,878.45	21	(12,520.01)	19

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
47	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	UV exposure	Fails leak rate, damage to electronics	Design	Field Failure	243	2	35	16,476.08	30	164,604.68	NC
48	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	UV exposure	Fails sustained pressure requirement, damage to airframe	Design	Field Failure	270	1					
49	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	UV exposure	Fails sustained pressure requirement, damage to electronics	Design	Field Failure	216	3					
50	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Incorrect fastener torque during installation	Fails leak rate, damage to electronics	Installation	Field Failure	120	21	36	23,798.78	22	(6,422.70)	21
51	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Incorrect fastener torque during installation	Fails sustained pressure requirement, damage to airframe	Installation	Field Failure	150	11					
52	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Incorrect fastener torque during installation	Fails sustained pressure requirement, damage to electronics	Installation	Field Failure	120	21					

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
53	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Handling damage during installation	Fails leak rate, damage to electronics	Operation	Field Failure	192	4	37	30,645.98	17	28,983.83	NC
54	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Handling damage during installation	Fails sustained pressure requirement, damage to electronics	Operation	Field Failure	144	14					
55	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Handling damage during installation	Fails sustained pressure requirement, damage to airframe	Operation	Field Failure	180	6					
56	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Handling damage during operation	Fails leak rate, damage to electronics	Operation	Field Failure	144	14	38	16,476.08	30	43,153.73	NC
57	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Handling damage during operation	Fails sustained pressure requirement, damage to electronics	Operation	Field Failure	144	14					
58	Product X can survive outdoors for a minimum of 10 years	CMC cover develops cracks	Handling damage during operation	Fails sustained pressure requirement, damage to airframe	Operation	Field Failure	180	6					

Item Number	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Potential Effects of Failure	Origin	Detection Phase	RPN	RPN Rank	Failure Scenario	EFC ($)	EFC Rank	Economic Impact Value($)	EIV Rank
59	Product X can survive outdoors for a minimum of 10 years	Exterior paint scratched	Handling damage during operation	Fails leak rate, damage to electronics	Operation	Field Failure	72	38	39	21,968.10	24	37,661.70	NC
60	Product X can survive outdoors for a minimum of 10 years	Exterior paint scratched	Handling damage during operation	Fails sustained pressure requirement, damage to electronics	Operation	Field Failure	72	38					
61	Product X can survive outdoors for a minimum of 10 years	Exterior paint scratched	Handling damage during operation	Fails sustained pressure requirement, damage to airframe	Operation	Field Failure	90	30					
62	Product X can survive outdoors for a minimum of 10 years	Water penetration	Exterior paint not correctly applied	Fails leak rate, damage to electronics.	Manufacture	Field Failure	168	8	40	9,153.38	36	3,264.00	NC
63	Product X can survive outdoors for a minimum of 10 years	Water penetration	O-ring not installed correctly	Fails leak rate, damage to electronics.	Installation	Field Failure	128	18	41	27,436.35	19	85,668.15	NC

VITA

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