Abstract

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Adoption and insertion of new technologies and processes into systems is inherently risky. A cost model that forecasts the cost of risk associated with inserting new technology into a system has been developed. The model projects the cost of inserting new processes, projects the impact of the processes on the cost of risk for the system, and performs a cost-benefit analysis on the adoption of proposed new processes. The projected cost of failure consequences (PCFC) is defined as the cost of all failure events (of varying severity) that are expected to occur over the service life of the system. The PCFC is uncertain, and the potential positive impact of adopting new technologies into the system is to reduce the cost of risk and/or reduce its uncertainty. A case study that assesses the adoption of a lead-free solder control plan into systems that previously used tin-lead solder has been performed.

Assessing the Cost of Risk for New Technology and Process Insertion

By

Edwin Lillie

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
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Professor Peter Sandborn, Chair
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Dedication

This thesis is dedicated to my mother, father, and brother, who I am grateful for supporting me throughout these past 23 years of my life and education.

I would also like to dedicate this thesis to my friends and fellow graduate students that have supported me through my years at Maryland. I would not be the person I am today without their love and support.

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I would like to take the time to thank several people for making this thesis possible. First and foremost, I must thank Professor Peter Sandborn for all the time and effort he has invested in me, ever since I walked into his office as an undergraduate student attempting to get involved in research three years ago. Professor Sandborn took me on as a B.S./M.S. student, and I am very grateful for having him as an advisor.

I would like to thank Professors Patrick McCluskey and Linda Schmidt for serving on my advisory committee.

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Special thanks to all the professors and TAs that taught the classes I took, and the office staff in the department of mechanical engineering for keeping my education running smoothly.

Finally, I would like to thank all my friends that have made my five years in college park quite memorable. I will miss you guys.

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Chapter 1: Introduction

Failure is defined as "The inability of a system or component to perform its required functions within specified performance requirements" (IEEE 1991). A failure event can be characterized by two measures: the likelihood that the event will occur and the consequences (i.e., cost associated with the event) that are realized when the event happens. In this context, the factors of likelihood and occurrence outline the risk associated with a failure. Design engineers often think in terms of minimizing the likelihood of a failure, but how can the benefits to reducing the chances of a failure event occurring be quantified? Inherently, if the likelihood of failure is reduced, fewer failure events will occur, and the owner of the product or system will avoid spending money on mitigating the effects of the failures that have been prevented, but reducing the likelihood of failure is not free.

The goal of this thesis is to develop a model to analyze the cost implications, good or bad, of adopting new technology (or processes) in safety-critical systems. Will the new technology increase the safety and reliability of the system? If so, will the adopted technologies be cost effective, so that the reduction in the cost of risk is greater than the cost to adopt the new technology? Conversely, if the adoption of the new technology or processes is mandated (by customers or regulations), what are the cost ramifications of the mandate?

1.1 Introduction

The IEEE's Standard Computer Dictionary defines reliability as "The ability of a system or component to perform its required functions under stated conditions for a specified period of time" (IEEE 1991). Quality is defined as "The degree to which a system, component, or process meets specified requirements" or "The degree to which a system, component, or process meets customer or user needs or expectations" (IEEE 1991). The key difference between reliability and quality is that reliability includes a measure of time, whereas quality is assessed at a specific point in time (often the conclusion of the manufacturing process).

1.2 Cost of Quality Methods and Models

First, consider models used to calculate the cost of quality. How engineers calculate the cost of quality of a product has been in flux for the past half century. One of the most well-known models was first developed by Feigenbaum (1956) and divides quality costs into three entities: prevention cost, appraisal cost, and failure cost (P-A-F). The P-A-F model has been adopted by the American Society for Quality and is widely used in industry. In the P-A-F model, failure costs are often divided into internal failure costs: those costs that are dealt with before the product has reached the customer, and external failure costs: those costs that arise from defects that occur after the product has reached the customer (Vaxevanidis 2008). Thus, the goal of the P-A-F model is to determine the level of quality that minimizes the total cost of quality, i.e. the sum of prevention, appraisal, and internal and external failure costs.

Crosby (1979) takes a similar approach, defining the cost of quality as the sum of the Price of Conformance (PoC) and the Price of Non-Conformance (PoNC). PoC is the cost of ensuring a product meets performance requirements, and PoNC is the cost the manufacturer of the product incurs when a product fails to meet performance requirements. In Cosby's model the optimal cost of quality is defined by the defect rate that produces the lowest combined costs of PoC and PoNC.

Crosby and Feigenbaum's models assume that there exists an optimal (greater than zero), percentage of defective products that results in the optimal (lowest) cost of quality. Hence, according to Crosby and Feigenbaum it could be more cost effective to design a lower quality product. Deming (1986) breaks from Crosby and Feigenbaum by asserting that the best way to optimize the cost of quality is to strive to eliminate all defects. Deming argues that since the cost of selling defective products to the customer is inevitably so high, and compounded by difficult to measure metrics such as loss of reputation, companies should strive for 100% non-defective products.

Activity Based Costing (ABC) has also been incorporated into some cost of quality models. Tsai (1998) states that ABC can be incorporated into P-A-F model to better estimate overhead costs in prevention and appraisal activities. In Tsai's ABC approach, activities are divided into: value-added activities, those that directly contribute to customer satisfaction, and non-value-added activities, those that do not directly contribute to customer satisfaction. In Tsai's model, prevention activities are value-added while appraisal and failure (correction) activities are non-value-added.

The ABC methodology suggests eliminating non-value-added activities and spending more money on improving value-added activities.

Another method to calculate the effective cost of quality is to calculate yielded cost. Becker and Sandborn state “Yielded cost, in general, is described as cost divided by yield” (Becker and Sandborn 2001), where yield is the fraction of non-defective products. Therefore, the yielded cost per good part is higher than the unit cost of each part, as the yielded cost takes into account defective parts that cost money to create, but generate no value.

The models discussed in this section focus on attaching a value to manufacturing quality, i.e., the quality of the product when it completes the manufacturing process. These models do not assess the value of product quality over time (i.e., reliability).

The Taguchi Loss Function is a method of calculating the loss due to increased variation in a product. Taguchi’s equations state that the loss increases as product variation increases (Taguchi 1995).

1.3 Cost of Reliability Methods and Models

The cost of reliability is, in essence, the cost of quality over time. Sears developed a cost of reliability model by defining “development of unreliability in a product and the costs of correcting the unreliability” (Sears 1991). Sears focuses on the money spent to remove defects from the system. Sears assumes the failure rate of the system is proportional to the number of defects in the system and that by removing defects the failure rate of the system will decrease.

Barringer defines reliability as "the odds for failure free operation during a given interval…" (Barringer 1997). Thus, Barringer defines the cost of reliability as those costs that are used to keep the system free from failure, and the benefits of those costs are improved availability, decreased downtime and maintenance costs, and decreased secondary failure costs (Barringer 1991). Barringer explores how different maintenance practices impact the system life-cycle cost and reliability, and finds that good maintenance practices, such as fixing broken parts and other parts that have little remaining life, are more cost effective than only fixing broken parts when performing maintenance.

Hauge defines risk as "the product of the severity of a failure and the probability of that failure's occurrence" (Hauge 2001). Failures are ranked based on severity and likelihood of occurrence. Each failure is given a severity rating and occurrence rating of 1-5, with 5 being the worst. The severity and occurrence ratings are multiplied together to give a total magnitude of the risk due to the failure. Hague states that this method was used to manage risks of potential failures on the space shuttle and keeps risks below and acceptable level.

Perera and Holsomback also describe a NASA risk management approach in depth. NASA's goal is to prioritize risks based on likelihood and severity, with equal weight given to both factors. Perera and Holsomback state that risks can be identified from "fault-tree analysis results, failure modes and effects analysis (FMEA) results, test data, expert opinion, brainstorming, hazard analysis, lessons learned from other project/programs, technical analysis or trade studies and other resources H" (Perera and Holsomback 2005).

Sun et al. (2012) describe a software cost of reliability model that incorporates the severity level of failures. Sun et al. claim that the risk from a defect in software depends on both the failure rate of the defect and the severity level of the defect. According to Sun et al., the risk of a defect is defined as "the expected loss if [the defect] remains in the released software" (Sun et al. 2012). The total cost of risk of the program is the sum of all the expected losses due to all defects in the system. Then, Sun et al. compares the estimated reduction cost of risk with the cost of testing software for defects and reviewing the tests.

1.4 Cost of Risk

Another cost measure is the cost of risk. Liu and Boggs, in their paper on cable life and the cost of risk, define the cost of risk as "the cost to a utility associated with early cable failure" and the cost of failure as "the cost to replace the cable" (Liu and Boggs 2009). The cost of failure varies depending on how difficult it is to replace the cable as direct-buried cables are more difficult and expensive to replace than cables in a duct, for example. Hence, Liu and Boggs define the cost of risk as the cost of those failures that are early, that is those that occur before the end of the service life of the product.

1.5 Problem Statement

Consider a company that makes a product and has the option to adopt new technology, processes or methods into its business practices. These new technologies have the potential to increase the reliability of product, but at the cost of installing and onboarding one or more of the technologies. In other words, the company pays additional money upfront, but the benefit of these costs will not be realized until several years after the product has been in service. The obvious question here is: will adopting one or more of these technologies be cost-effective over the product's life cycle? In this instance life cycle of a product is the time period starting with its manufacture through the end of its service life. The problem can be concisely framed as:

Determine the life-cycle cost of a system associated with the adoption of a combination of technologies, processes and/or methodologies, where the adoption may be mandated and the life-cycle cost ramifications include the projected cost of failure consequences (PCFC). The best combination will be the most cost-effective combination that satisfies the system owner's reliability requirements.

In order to solve this problem, several things have to be done: first, calculate the current, pre-technology insertion, cost of risk for the system, second, determine the cost of inserting the selected technologies, third, calculate how the new technology will impact the cost of risk during the entire service life of the product, and finally, determine with a given level of confidence that inserting the new technology will or will not be cost effective.

There are several issues with applying the existing cost of quality models to the problem stated above. First, the Crosby and Feigenbaum models do not account for multiple types, and severities, of failure. Although all non-conforming parts may entail negative consequences and costs for the system owner, all non-conformities are not necessarily equal. Second, the Crosby and Feigenbaum models do not account for failures during the service life of the product, in other words they deal with quality, but not reliability.

Also, the existing models do not include decision making parameters for technology insertion. While the Crosby and Feigenbaum models may be able to outline the general ideas one would use for calculating the cost of risk for a given system, one would need a decision making framework in order to solve the technology insertion problem, a framework that would outline the cost benefits, and uncertainties with adopting new technology or practices into a system.

Finally, none of the existing models attach uncertainty to risk. It is intuitive that when calculating the cost of risk due to failures that have a probability of occurring, there will be an uncertainty attached to the calculated cost. It would be useful to have a model that could include uncertainty as part of its calculation and then make a business case for adopting or not adopting the technology with a level of confidence.

In summary, the existing models provide the foundations and fundamental ideas for calculating the cost of risk, but in order to develop a model that could readily be applied to solve the technology insertion problem, much work remains to be done.

1.6 Research Plan and Tasks

In order to develop and test the new model, the following steps have been performed:

1. Carefully define the technology adoption problem and state assumptions.
2. Conduct a comprehensive survey on work already completed in fields such as risk analysis, cost of quality, and others. Analyze the current body of knowledge and determine if it can solve the problem. If it cannot, identify what must be developed in a new model to solve the technology adoption problem.
3. Develop a model to solve the technology adoption problem.
4. Test the model and determine its applicability by using it to perform case studies in relevant fields.
5. Analyze the completed model and the case study. Determine the strengths and weaknesses of the model and identify future to further improve the model.

Chapter 2: The Technology Insertion Cost of Risk Model

This chapter describes in detail how the technology insertion cost of risk model is formulated. First, the primary sources that served as a background for portions of the architecture of the model are discussed, and then the model is described. Additionally, potential sources of data for the model are described, including how best to interpret the data for use in the model.

2.1 Calculating the Projected Cost of Failure Consequences (PCFC)

The first task of this model is to calculate the Projected Cost of Failure Consequences (PCFC) for the fleet of products that the model is analyzing. In this thesis, PCFC is defined as the cost that the fleet owner expects to incur over the service life of the product due to failures of members of the fleet. We assume that the system owner is under contract requiring the system to operate for a set amount of time, for example 20 years of service, so each field failure must be met with corrective action to keep the fleet of products performing. Failure costs include but are not limited to warranty costs, cost of repairing failed units, cost of replacing failed units, and loss of performance due to system downtime. PCFC includes both damages that result from failure events (damage to property, loss of life, delays in schedule), and repair or maintenance costs to return the system to operating condition so it can carry out the remainder of its service life.

Systems can fail in different ways, and all failures do not necessarily have the same financial consequences to the owner. A product failure that requires maintenance (repair) might cost less than a failure that is so severe that the system owner must replace the unit. The system owner needs to predict the cost of all the failure events that are expected to occur over the life of the fleet of products, taking into account that those products can fail multiple times, in multiple ways, and with different financial consequences of failure depending how the product fails.

Taubel (2006) calculates a total mishap cost by plotting the known costs associated with mishaps versus the probability of mishap for different severities of mishap (e.g., Figure 1), and then determining the area under the curve connecting the points. In Taubel's study, the definition of mishap derives from the Department of Defense's Military Standard 882C: "An unplanned event or series of events resulting in death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment." (Mil-STD-882C 1979). Note that while Taubel's model works with mishaps, the model developed in this thesis is built around failures, as defined by the IEEE standard dictionary (IEEE 1991). In the Taubel model, each severity level of a mishap has a distinct cost and an associated probability of occurrence of the mishap. For example, Taubel defines a severity 3 failure as a failure that will cost $10,000-$100,000 to resolve. Taubel demonstrates his model using past marathon injury data to predict the future severity (cost) and likelihood of occurrence of various injuries. In his example a severity level 3 failure would be one where a runner is sent to the hospital but does not have to be admitted. The area under the line defined by the severity levels of failure is the expected mishap cost for one race.

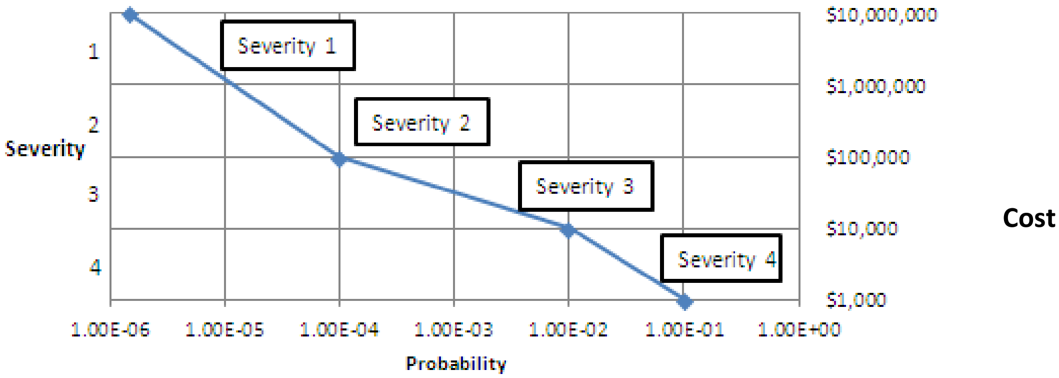

Figure 1: The multiple severity method (Taubel 2006)

A model similar to Taubel's multiple severity method is used in this thesis to determine the overall cost of mishaps for a product before and after mitigation activities are used. A mitigation activity is a process that may reduce the overall expected number of mishaps at certain severity levels. Each mitigation activity is assumed to affect a specified set of severity levels and does not change the probability of a failure for the other severity levels. For example, to prevent mishap events from occurring during a marathon, one might fill potholes in the road prior to the race; this impacts the probability of occurrence of mishaps due to runners tripping (e.g., sprained ankles or broken legs), but has no impact on the probability of mishaps such as heat exhaustion or heart attacks.

The model in this thesis calculates expected number of failures at each severity level rather than calculating the probability of failure at each severity level. It does so because some failures that may occur more than once during the life of the product, hence the cost of (multiple) failures is accounted for when calculating PCFC.

2.2 The Source of PCFC Data

An important consideration for the implementation of a cost of risk model is how to obtain data about a system, i.e., the ways a system can fail, and the cost and likelihood of occurrence of those failures. One source of this data is a Failure Modes, Mechanisms, and Effects Analysis (FMMEA) report. A FMMEA categorizes failure events and assigns each event a rating for its severity and likelihood of occurrence. Also, a Failure Modes and Effects Analysis (FMEA) or a Failure Modes Effects and Criticality Analysis (FMECA) could also be used a source of data on the severities and frequencies of the ways a system could fail. A FMEA is very similar to a FMMEA, except that a FMEA does not analyze the mechanisms associated with each failure. Additionally, a FMECA is an extension of a FMMEA that includes a criticality analysis.[1]

For example, the Army's "Failure Modes Effects and Criticality Analysis (FMECA) Manual for Command, Control, Communications, Computer Intelligence, Surveillance, and Reconnaissance Facilities" is one example of how a FMMEA or FMECA can be used as a source of data on failure severities and occurrence rates (MIL-STD-882C 1993). Tables 1 and 2 show the Army's ten severity and occurrence ratings respectively. In a FMECA report, each failure a system could experience would be assigned failure severity and occurrence ratings from these scales.

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[1] Criticality analysis is a method of prioritizing failures after each failure is assigned a severity and occurrence rating, but for the scope of this thesis, a criticality analysis is not needed.

Table 1: Army severity rankings, reproduced from (TM 5-698-4 2006)

Ranking	Effect	Comment
1	None	No reason to expect failure to have any effect on Safety, Health, Environment or Mission.
2	Very Low	Minor disruption to facility function. Repair to failure can be accomplished during trouble call.
3	Low	Minor disruption to facility function. Repair to failure may be longer than trouble call but does not delay Mission.
4	Low to Moderate	Moderate disruption to facility function. Some portion of Mission may need to be reworked or process delayed.
5	Moderate	Moderate disruption to facility function. 100% of Mission may need to be reworked or process delayed.
6	Moderate to High	Moderate disruption to facility function. Some portion of Mission is lost. Moderate delay in restoring function.
7	High	High disruption to facility function. Some portion of Mission is lost. Significant delay in restoring function.
8	Very High	High disruption to facility function. All of Mission is lost. Significant delay in restoring function.
9	Hazard	Potential Safety, Health or Environmental issue. Failure will occur with warning.

10	Hazard	Potential Safety, Health or Environmental issue. Failure will occur without warning.

Table 2: Army occurrence ratings, reproduced from (TM 5-698-4 2006)

Ranking	Failure Rate	Comment
1	1/10,000	Remote probability of occurrence; unreasonable to expect failure to occur
2	1/5,000	Very low failure rate. Similar to past design that has, had low failure rates for given volume/loads
3	1/2,000	Low failure rate based on similar design for given volume/loads
4	1/1,000	Occasional failure rate. Similar to past design that has had similar failure rates for given volume/loads
5	1/500	Moderate failure rate. Similar to past design having moderate failure rates for given volume/loads
6	1/200	Moderate to high failure rate. Similar to past design having moderate failure rates for given volume/loads
7	1/100	High failure rate. Similar to past design having frequent failures that caused problems

8	1/50	High failure rate. Similar to past design having frequent failures that caused problems
9	1/20	Very high failure rate. Almost certain to cause problems
10	1/10+	Very high failure rate. Almost certain to cause problems

2.3 Technology Insertion Cost of Risk Model

Next we describe the model itself. An overview of the steps in the model is shown in Figure 2.

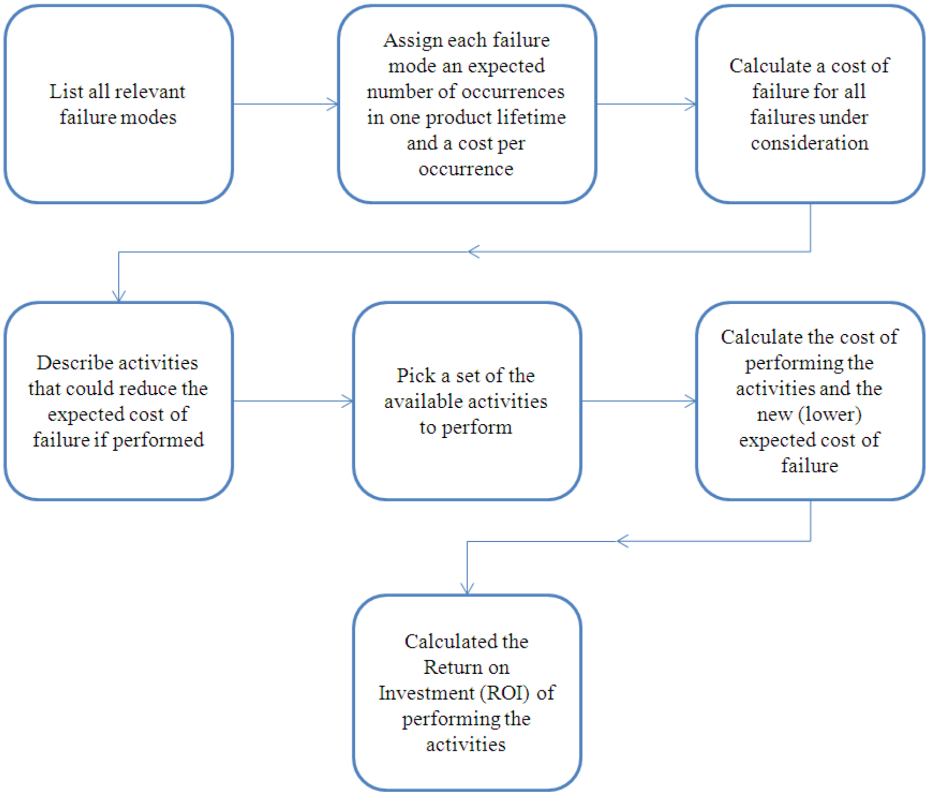
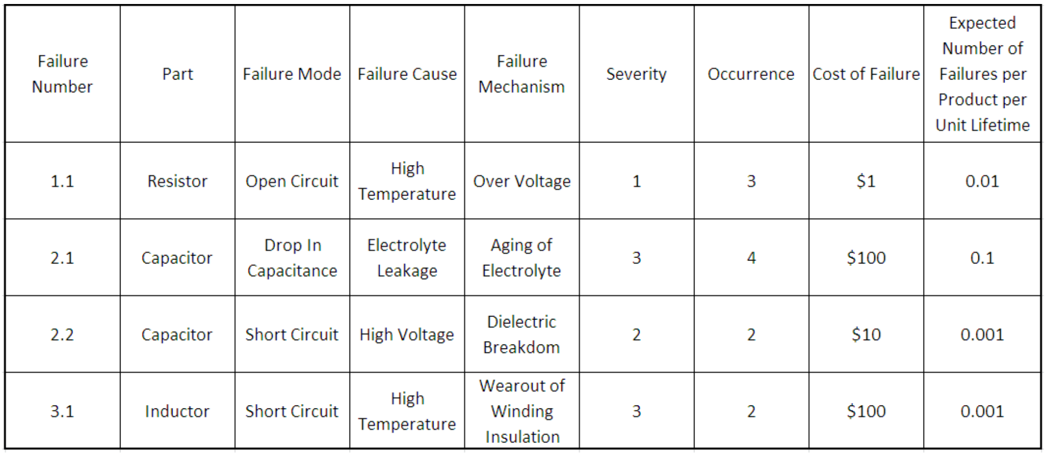


Figure 2: Modeling Steps

The model's first task is to organize the given failure data. Let's say that the user wants to analyze a system composed of electric parts. Before the PCFC can be calculated, each relevant failure must be identified and described by: the part affected by the failure, and by the failure mode, cause, and mechanism associated with an occurrence of that failure. An example of the data for four failures associated with three types of parts is shown in Table 3, which shows, in this example, that capacitors are associated with two distinct failure types while resistors and inductors are only impacted by one type of failure.

Table 3: Sample part-specific failure data

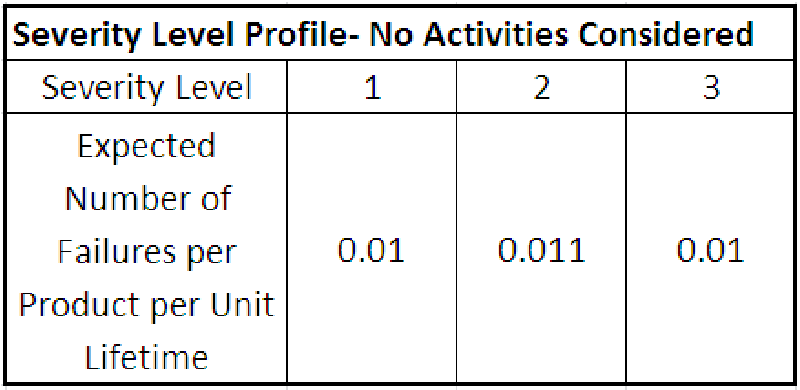


Failure Number	Part	Failure Mode	Failure Cause	Failure Mechanism	Severity	Occurrence	Cost of Failure	Expected Number of Failures per Product per Unit Lifetime
1.1	Resistor	Open Circuit	High Temperature	Over Voltage	1	3	$1	0.01
2.1	Capacitor	Drop In Capacitance	Electrolyte Leakage	Aging of Electrolyte	3	4	$100	0.1
2.2	Capacitor	Short Circuit	High Voltage	Dielectric Breakdom	2	2	$10	0.001
3.1	Inductor	Short Circuit	High Temperature	Wearout of Winding Insulation	3	2	$100	0.001

Additionally, each failure is described by a severity level and an occurrence factor, each of which correspond to a numerical value of the cost associated with an occurrence of the failure and the expected number of failures to occur over the service life of the product.

Next, the number of failures expected to occur over the service life of the product at each severity level are calculated. The collective expected number of failures for each severity level is called the severity level profile in the model. At this stage in the modeling process we are creating the initial severity level profile, as no activities, options the user could choose to implement to reduce the likelihood of failure, have been considered yet. A sample severity level profile is shown in Table 4.

Table 4: Number of Failures Expected to Occur at each Severity Level



Severity Level Profile- No Activities Considered			
Severity Level	1	2	3
Expected Number of Failures per Product per Unit Lifetime	0.01	0.011	0.01

The calculation of the expected number of failures per product per unit lifetime for each distinct severity level is given by equation (1):

$$f_{severity\ level\ i} = \sum_{j=1}^{n} f_j \qquad (1)$$

where:

f = Expected number of failures per product per unit lifetime

i = Severity level under consideration

n = Number of failures of severity level i

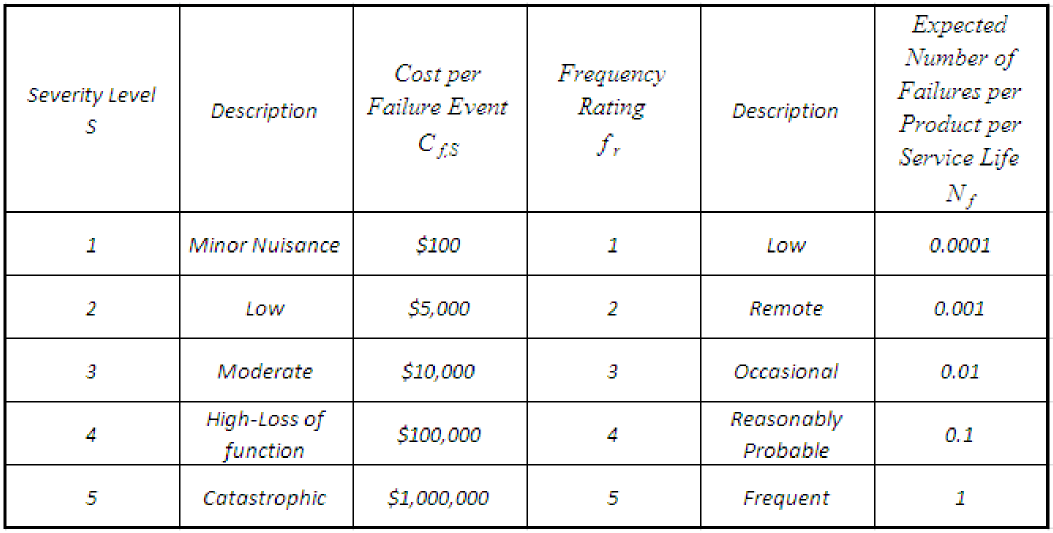
2.4 Using the System Failure Data to Determine the Initial PCFC

Now, let’s use the data obtained from a FMMEA to calculate the PCFC. Each failure the system can experience is described by two characteristics: the severity of failure and the frequency of occurrence of that failure. FMMEAs or FMECAs are great sources of data on the ways a product or system can failure, the relative likelihood of those failures occurring, and the severity of those failures. By severity, we mean the cost of the actions that the system or product owner will have to take to correct or compensate for the effects of a failure after it has occurred.

Most FMMEAs in use today qualitatively describe severity and frequency of failure, whereas to be used in this mathematical model each failure's severity and frequency must be quantitatively defined, so that each failure has a severity and frequency describing it that tell us: 1) the expected cost that the system owner will incur for every instance of the occurrence of that failure, and 2) the number of times the failure is expected to occur over the service life of the system. As shown in Table 3, the right-most columns are the assigned values for the expected cost of each failure and the number of failures to occur.

For example, in the FMMEA used for the case study in the next chapter of this thesis, severity of failure is rated on a scale of 1-5, with a severity 1 failure defined as a minor nuisance and a severity 5 failure defined as a catastrophic failure. But, each of these severities must be assigned a specific cost associated with an occurrence of that severity. Note that this cost is the average expected cost, as we assume that the cost of a certain severity of failure will be the same every time the failure occurs. This cost may also have uncertainty associated with it. Likewise the FMMEA used in the case study describes the frequency of failure on a qualitative scale of 1-4, with frequency 1 failures described as low and frequency level 5 failures described as frequent. To be used in the model, each frequency rating needs to be translated into an expected number of times that failure will occur over the lifetime of the product. An example conversion scale is shown in Table 5.

Table 5: Example conversion of qualitative FMMEA ratings to quantitative ratings



Severity Level S	Description	Cost per Failure Event $C_{f,S}$	Frequency Rating f_r	Description	Expected Number of Failures per Product per Service Life N_f
1	Minor Nuisance	$100	1	Low	0.0001
2	Low	$5,000	2	Remote	0.001
3	Moderate	$10,000	3	Occasional	0.01
4	High-Loss of function	$100,000	4	Reasonably Probable	0.1
5	Catastrophic	$1,000,000	5	Frequent	1

It is up to the system owner how to transform FMMEA ratings to numerical values of cost and expected number of failures. The cost associated with a certain severity of failure and expected number of failures for a given frequency rating could vary based on several factors including: operating conditions, the context the system is being used in, and the length of the service life. In the example outlined by Table 5, the conversion was performed with an exponential scale, so that a severity level 1 failure has a cost of $1 per failure event, a severity level two has a cost of $10 per event, and so on. Equations (2) and (3) define the conversion scales for frequency to number of expected failures and severity level to cost per failure event, respectively.

$$N_f = (0.001)10^{f_r - 1} \tag{2}$$

where:

N_f = Number of expected failures per product per unit lifetime

f_r = Qualitative occurrence rating, typically from a FMMEA

$$C_{f,S} = (10)10^{S-2}$$

(3)

where:

S = Severity level under consideration

$C_{f,S}$ = Cost per failure event at severity level S

Equation (2) which takes the qualitative occurrence rating from a FMMEA and calculates expected number of failures, is just one method that someone could use to generate an expected number of failures to occur over a product's service life. One could also use physics-of-failure models or data-driven methods to obtain the expected number of failures. Applying the loading conditions to a physics-of-failure model of each FMMEA could be used to determine the expected number of failures. Similarly, if failure data for a certain set of conditions exists, that data could be used to obtain the expected number of failures. For example, in the case study presented in Chapter 3, some of the failures calculate the expected number of failures using a Weibull distribution based on the number of thermal cycles the product or system is expected to experience over its service life. Equation (4) calculates the chance a failure will occur using the cumulative distribution function of the Weibull distribution.

$$F(c) = e^{(\frac{-(c-\gamma)}{\eta})^{\beta}}$$

(4)

where:

c = number of thermal cycles per product service life

$F(c)$ = Value of the Weibull cumulative distribution function at c

β = Weibull shape parameter

η = Weibull scale parameter

γ = Weibull location parameter

Using equation (4), we can now calculate the number of failures expected to occur over the service life of the product for failure listed in the FMMEA.

Now that the model has an expected number of occurrences for each failure severity, and a cost associated with each occurrence at every severity, the PCFC for the system can be calculated. Figure 3 shows a plot of the expected number of failures and cost associated with each failure for five severity levels. The vertical axis is the number of failures expected to occur per product per service life. The service life is the required life the system, expressed in years or cycles. The horizontal axis is the cost per failure event. Figure 3 is clearer when the two axes are converted to log scales, as shown in Figure 4. To further simplify the graph we represent the lines between severity levels as straight lines as shown in Figure 5. For the remainder of this thesis graphs of failures will use log-log axes with straight line graphical simplifications, however, the analysis performed assumes that the plots look like Figure 4.

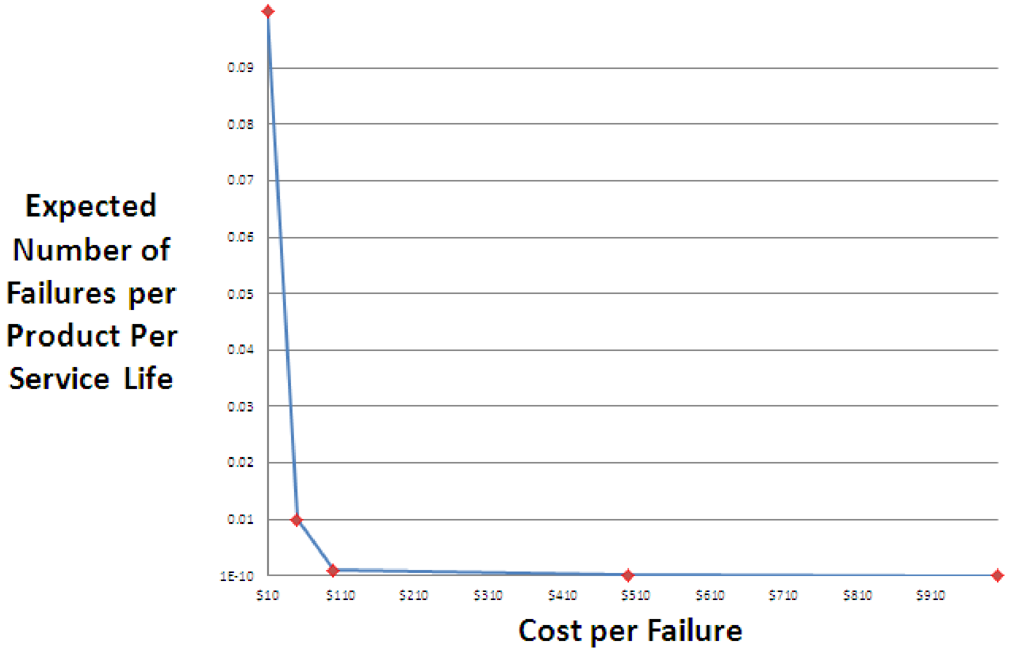


Figure 3: Expected number of failures vs. cost per failure graphed on linear axes

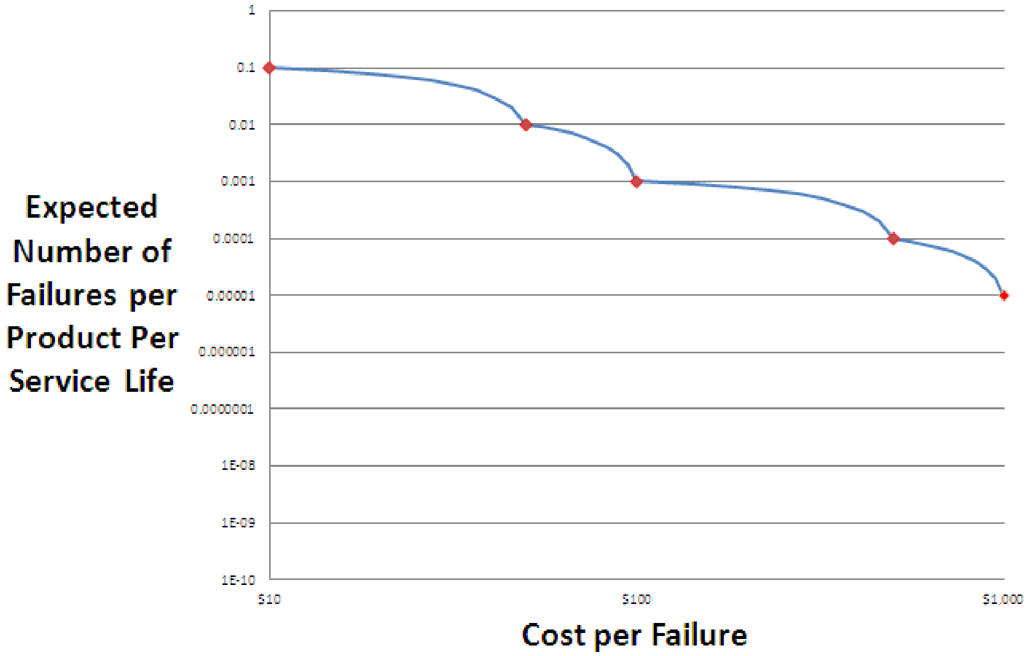


Figure 4: Expected number of failures vs. cost per failure graphed on logarithmic axes

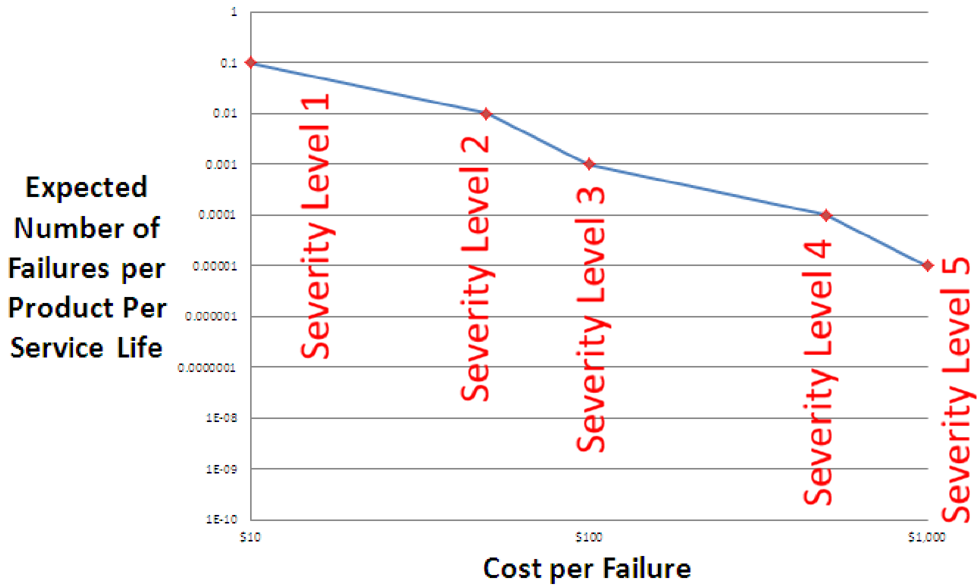


Figure 5: Expected number of failures vs. cost per failure graphed on logarithmic axes with straight line simplification

The cost and number of failures for each severity level are connected and form a curve. The area under this curve is the PCFC for the system. This area is the integral of the line connecting the points evaluated at from the point at severity level 1 to the point at severity level 5. The model determines the total area under the curve by calculating the area under the curve between consecutive severity levels, say 1 and 2, and summing up all these discreet areas to obtain the PCFC for the entire system. Equation (5) describes the calculation of the overall PCFC:

$$Initial\ PCFC = \int_{E_1}^{E_n} C(x)dx \tag{5}$$

where:

E_1 = Expected number of severity level 1 failures

E_n = Expected number of severity level n failures

n = Number of severity levels under consideration + 1

C(x) = Cost of a failure event occurring at severity level *x*

Note that this area represents the area under the curve in figure 3, where cost and severity of failure are graphed on linear axes.

Since the PCFC is the area under the curve in Figure 4, the model calculates the PCFC by calculating the area under each trapezoid formed by the points in the curve and summing all the areas. Equation (6) shows how to calculate the areas under all the trapezoids and Figure 6 illustrates Equation (6) in progress after it has calculated the area under the first two trapezoids.

$$\mathit{Initial\ PCFC} = \sum_{i=1}^{n} E(i+1)\big(C(i+1)-C(i)\big) + 0.5(E(i)\,\big(C(i+1)-C(i)\big) \quad (6)$$

where:

n = number of points on the curve + 1

E(x) = Expected number of failures per product per unit lifetime of point (severity level) *x* on the curve

C(x) = Cost of each failure of point *x* on the curve

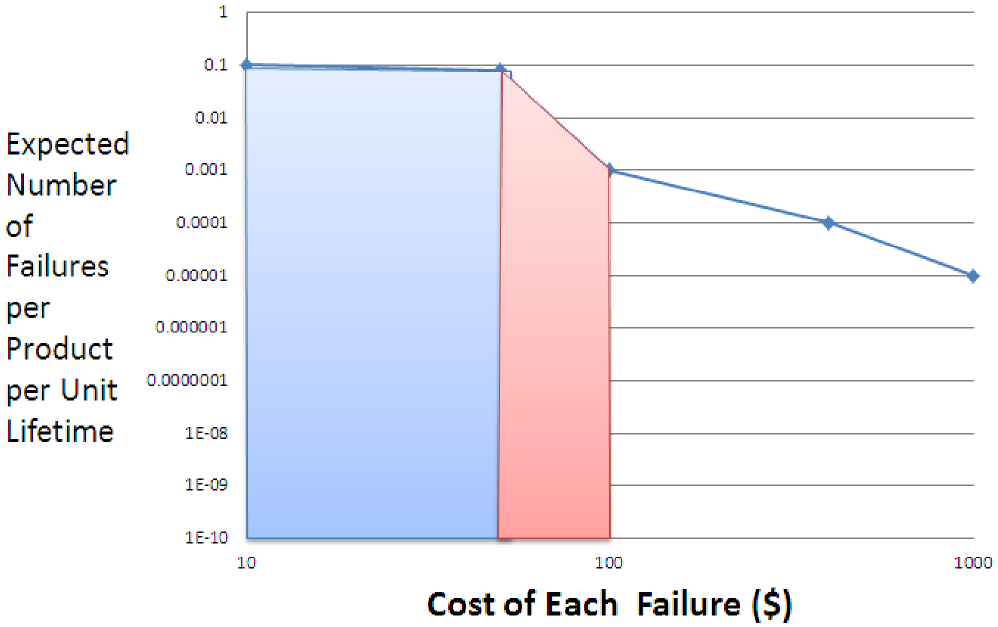


Figure 6: Calculating the area curve by calculating the area under each trapezoid formed by the points on the curve

2.5 Activities that Modify the Expected Number of Failures

Now that the PCFC for the system has been calculated, the activities that can potentially lower the cost of the system can be considered. An activity is sub-process, process, or group of processes (or possibly technology or material) that when performed (or applied) changes the number of expected failures over the service life of the product. Activities can be performed at multiple levels of rigor; rigor is the detail or depth at which the activity is performed. Performing an activity at a higher level of rigor has the potential for a greater reduction in the number of expected failures, but it will cost more.

Activities can affect specific failure modes, failure mechanisms, failure causes, and parts. If an activity is defined to affect the mode, mechanism, cause, and part that corresponded to a failure in the FMMEA used to create the initial severity level profile, then if that activity is performed, the number of expected failures will drop. Equation (7) shows the calculation of the new expected number of failures after a number of activities are performed.

$$N_{f-f} = (N_{f-i}) \prod_{i=1}^{m} P_R(i, R)$$

(7)

where:

$N_{f\text{-}f}$ = Number of failures expected to occur over the service life of the product for a particular failure listed in a the FMMEA after considering activities

$N_{f\text{-}i}$ = Number of failures expected to occur over the service life of the product for a particular failure listed in a the FMMEA before considering activities

$P_R(i, R)$ = Fractional reduction in the expected number of failures to occur over the service life of the product do to performing activity i

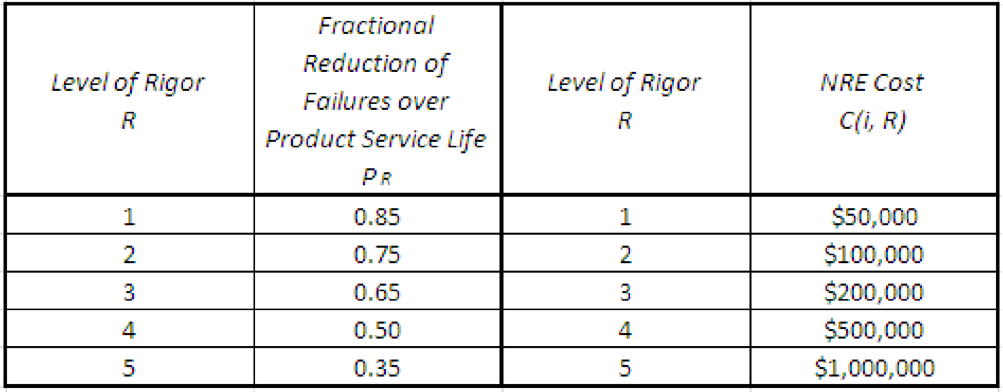
m = Number of activities performed that affect the failure under consideration

R = The level of rigor activity i is performed at

In order to describe an activity to be used in the model, the user must define the reduction in failures over the service life of the product, the non-recurring (NRE) cost for each level of rigor, and state which failure modes, failure mechanisms, failure causes, and parts the activity will impact if performed. Note that an activity can affect any number of modes, causes, mechanisms, and/or parts. Table 6 shows a sample activity's reduction of failure and NRE cost data for its five levels of rigor.

Table 7 shows a sample of modes, mechanisms, causes, and parts that an activity could impact.

Table 6: Levels of rigor and corresponding reduction of failures and NRE cost for an example activity



Level of Rigor R	*Fractional Reduction of Failures over Product Service Life P_R*	*Level of Rigor R*	*NRE Cost C(i, R)*
1	0.85	1	$50,000
2	0.75	2	$100,000
3	0.65	3	$200,000
4	0.50	4	$500,000
5	0.35	5	$1,000,000

Table 7: Selection of modes, causes, mechanisms, and parts an activity affects

	Failure Modes		Failure Causes		Failure Mechanisms		Parts
☐ FALSE	Open Circuit/ Cracked Solder Joint	☑ TRUE	Temperature Cycling	☑ TRUE	Fatigue	☑ TRUE	PCB-Capacitor Through Hole Solder Joint-Large
☑ TRUE	Intermittent Open Circuit/ Cracked Solder Joint	☑ TRUE	Extreme Temperature or Vibration	☐ FALSE	Shock	☑ TRUE	PCB-Wire Through Hole Solder Joint-Large

The investment cost associated with an activity is the cost of performing the activity at the specified level of rigor, and is comprised of only non-recurring engineering (NRE) cost. The user of the model specifies which activities to perform, and the levels of rigor at which activities are performed. The cost of performing all activities, called the *Total Implementation Cost*, is calculated according to equation (8):

$$Total\ Implementation\ Cost = \sum_{i=1}^{n} C(i,R) \qquad (8)$$

where:

i = the activity under consideration

n = The number of activities being performed

R = The level of rigor activity *i* is performed at

C(i,R) = Cost of performing activity *i* at level of rigor *R*

2.6 Calculating the Effect of Activities on the Expected Number of Failures

By performing activities, the user intends to reduce the number of failures the system will experience over one lifetime, in the hope of avoiding some of the costs associated with the occurrence of these failures. As shown in Table 6, performing an activity at level of rigor *R* will reduce the number of times a failure is expected to occur. However, the model determines which failures listed in the FMMEA each activity affects by checking if that failure's mode, mechanism, cause, and part are impacted by the activity. For example, consider the activity described by the characteristics in Tables 6 and 7 performed at a level of rigor of 3. A failure described by the mode: Intermittent Open Circuit/ Cracked Solder Joint, cause: Extreme Temperature or Vibration, mechanism: Fatigue, and part: PCB- Wire

Through Hole Solder Joint- Large, would see its expected number of failures over one system service life reduced by 35% because all of four of its defining characteristics (mode, cause, mechanism, and part) are affected by the activity.[2] But, a failure whose failure mechanism was Shock would see no reduction in its expected number of failures because the activity does not impact failures whose failure mechanism is Shock. Equation (9) describes the calculation of the effect of activities:

$$N_{F,f} = N_{F,i}(P_R) \tag{9}$$

where:

$N_{F,f}$ = The number of failures expected to occur after the activity has been performed

$N_{F,i}$ = The number of failures expected to occur before the activity has been performed

P_R = The fractional reduction of failures at level of rigor R, note that P_R could be greater than one, meaning that an activity causes the number of expected failures to increase.

The model performs the calculation in equation (6) for each activity on every failure listed in the FMMEA whose mode, cause, mechanism, and part are all impacted by the activity.

2.7 Calculating the PCFC after Activities have been Performed

Now that a set of activities has been described and implemented, the model once again calculates the PCFC for the system. But, now that activities are considered, the expected number of failures the system will experience over one

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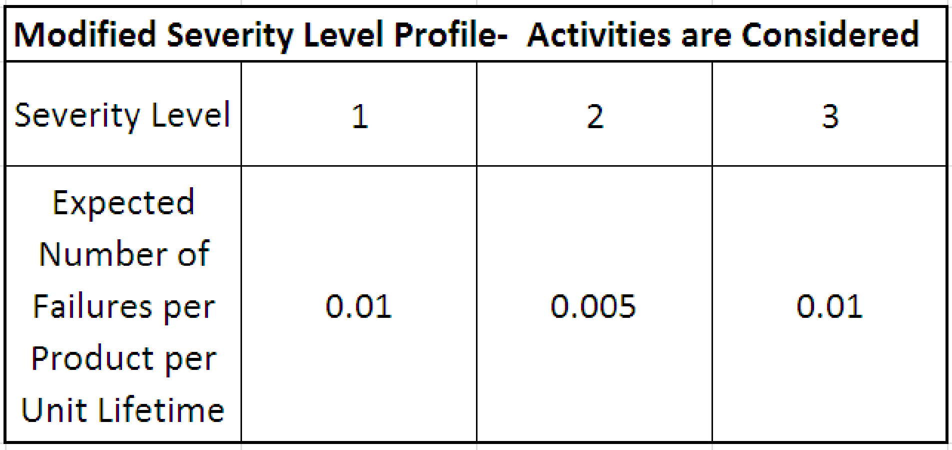
[2] The fractional reduction of failures over product service life for this activity at level of rigor 3 is 0.65, meaning that the number of expected failures is multiplied by 0.65, hence a reduction of 35%.

lifetime may be lower due to the activities having been performed. The failures listed in the FMMEA that have been affected by activities may have a lower expected number of failures than they did before activities were considered.

First the model calculates the number of failures expected to occur at each severity level, as outlined in equation (1), except now some of the failures are expected to occur fewer times over one product service life. Using equation (1) the model generates the modified severity level profile, as shown in Table 8:

Table 8: Modified expected number of failures at each severity level



Modified Severity Level Profile- Activities are Considered			
Severity Level	1	2	3
Expected Number of Failures per Product per Unit Lifetime	0.01	0.005	0.01

Next, the model uses the new expected number of failures to calculate expected PCFC of the system using equation (10).

$$Modified\ PCFC = \int_{E_{1-f}}^{E_{n-f}} C(x)dx \qquad (10)$$

where:

E_{1-f} = Expected number of severity level 1 failures after activities are considered

E_{n-f} = Expected number of severity level n failures after activities are considered

n = number of severity levels under consideration + 1

C(x) = cost of a failure event occurring at *x*

Now that the modified PCFC has been determined, the difference between the initial PCFC and the modified PCFC, called the *Reduction in Failure Cost* is calculated. Equation (11) defines the calculation:

$$Reduction\ in\ Failure\ Cost = Initial\ PCFC - Modified\ PCFC \qquad (11)$$

The *Reduction in Failure Cost* can be graphically represented as the difference in the areas under the curves in 7. The top curve is the expected number of failures versus PCFC before activities are considered, and the bottom curve is the expected numbers of failures versus PCFC after activities are considered. In Figure 8, the reduction in area under the curves is shaded.

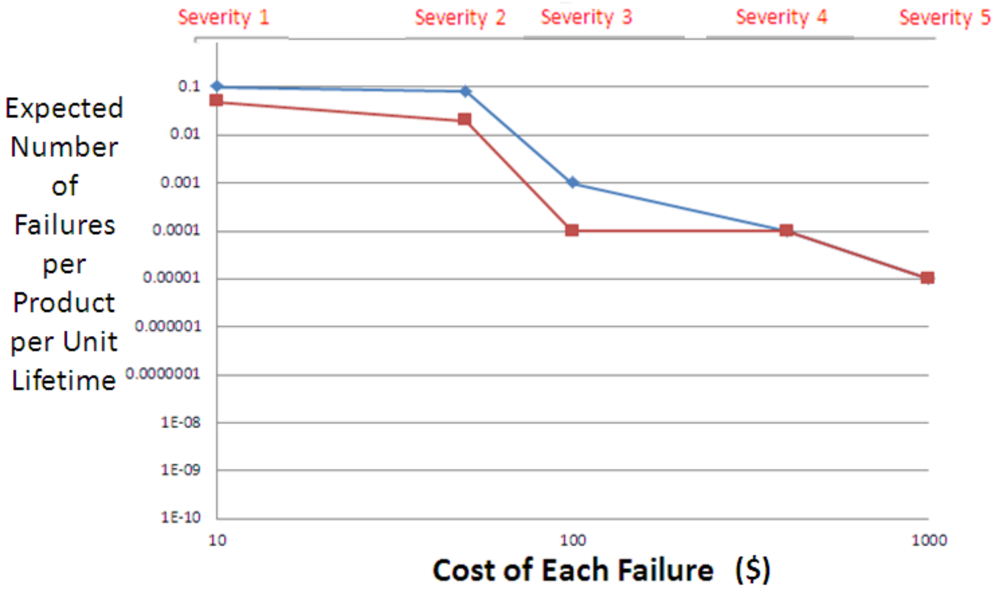


Figure 7: The blue (top) curve represents the number of failures per product per unit lifetime at each severity level before activities are considered, and the red (bottom) line represents the number of expected failures after activities are performed.

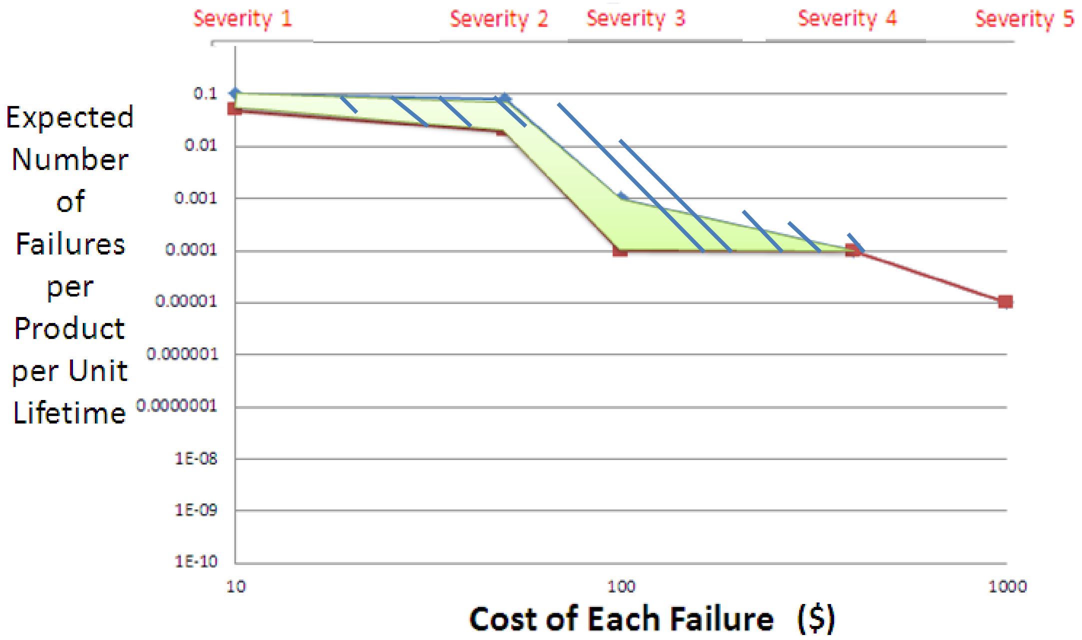


Figure 8: The area between the curves is the reduction in expected PCFC to be incurred per product per unit lifetime

2.8 Calculating Return on Investment

The final step in the model is to calculate the *Return on Investment* or ROI. The ROI is defined as the difference between return and investment divided by investment. In the case of this model, the investment is the money spent on performing activities, the *Total Implementation Cost*, and the return is the PCFC that will be avoided because activities have been performed, the *Reduction in Failure Cost*. Equation (12) defines ROI in terms of this thesis:

$$Return\ on\ Investment\ (ROI) = \frac{Return - Investment}{Investment}$$

$$= \frac{Reduction\ in\ Failure\ Cost - Total\ Implementation\ Cost}{Total\ Implementation\ Cost}$$

(12)

2.9 Uncertainty in the Model

The model is designed to handle several types of uncertainty. The model allows for uncertainty in the effectiveness of activities, the number of failures expected to occur over the service life at each severity level, and the cost of performing activities.

The effectiveness of activities is defined by equation (9). In equation (6) the fractional reduction of failures, P_R, is a fraction (usually between 0 and 1, but not necessarily because an activity could make a product more likely to fail) that is multiplied with the initial number of failures to calculate the final number of failures after the activity has been performed. However, a person using this model might be uncertain over how effective the activities will be at reducing the number of failures, and hence uncertain in the value of P_R for each activity. To account for uncertainty, the model allows P_R to be defined as a distribution. For example, P_R could be a triangular distribution with a mode of 0.50, a low value of 0.25, and a high value of 0.75.

Similarly, one could also define the number of failures expected to occur over one service life of the system and the cost of performing an activity as a distribution. Thus, in one run of the model, the model samples the distributions defining certain parameters to obtain a value for those parameters for that particular trial. By running many trials (each trial could represent one instance of the system) a range of values for the ROI is obtained representing the value of the activities to the population of systems. Figure 9 shows an example where the model has been run 10 times with uncertainties. Note that there is uncertainty in the blue curves because the number of expected failures before activities are applied is uncertain, and there is uncertainty in the red curves because the effectiveness of activities is uncertain. Figure 10 shows the resulting histogram of ROIs from 1000 trials.

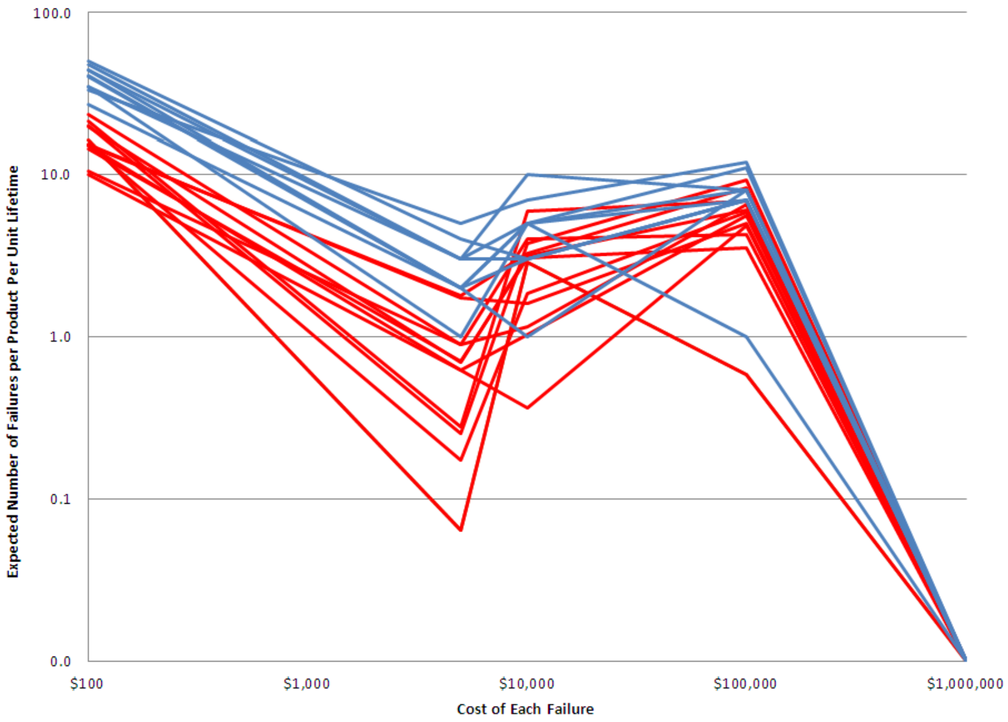


Figure 9: Results of 10 trials when certain parameters in the model are distributions and sampled every trial.

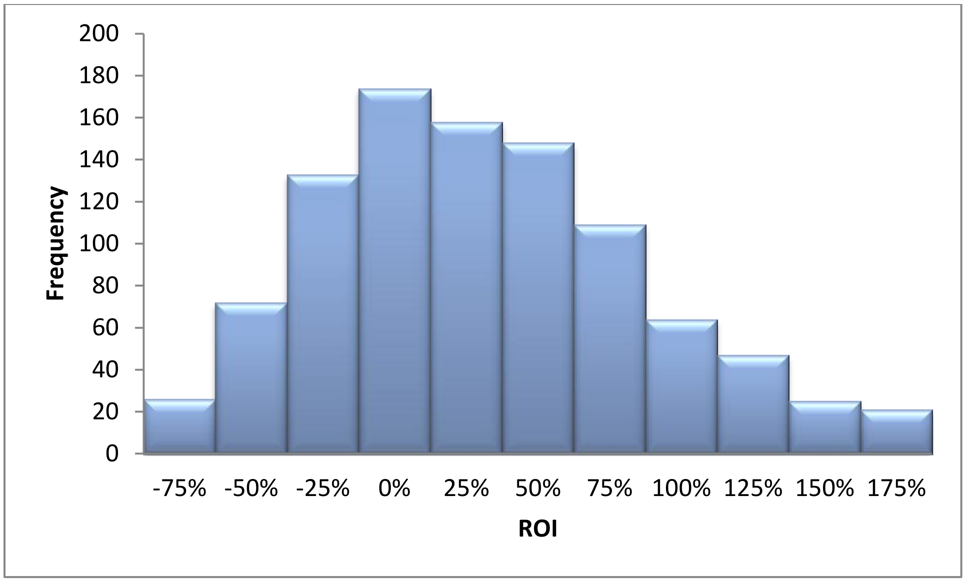


Figure 10: Histogram of the values of ROI for 1000 trials

2.10 Implementation

The model developed in this thesis was constructed on a spreadsheet and programmed with Microsoft Excel Visual Basic.

Chapter 3: Lead-Free Solder Control Plan Case Study

On July 1, 2006 the European Union's Restriction of Hazardous Substances (RoHS) Directive and Waste Electrical and Electronic Equipment (WEEE) Directive went into effect, banning the use of lead in electronics and electrical equipment. Mueller et al. (2005) outlines environmental and technological issues associated with using lead-free solder in electronic assemblies. Removing lead from electronics is generally perceived to benefit the environment and society because electronics often end up in landfills when they are discarded, and the public fears that lead from discarded parts will contaminate groundwater. As a result of banning lead, non-traditional solders such as SnCu must be used in electronics. Therefore, product developers must qualify their products (and processes) when replacing tin-lead (SnPb) solder with lead-free solder (e.g., SnCu):

> "Reliability testing becomes necessary for compliance with the needs of the product manufacturers and users and have to be carried out to identify the sources of errors caused by the many new material combinations with their intermetallics, unknown material behavior at the higher soldering temperatures and the whisker phenomenonon Sn plated surfaces" (Mueller et al. 2005).

Mueller et al. also describes the dangers of tin whiskers and the need for more research to prevent the whiskers from creating short circuits when tin platings are used.

Considerable work has been done on predicting the reliability of lead-free solder used in solder joints. Lau et al. (2003) defines reliability of a solder joint as "the probability that the solder joint will perform its intended function for a specified period of time, under a given operating condition, without failure" (Lau et al. 2003). Lau et al. describes several models for accelerated testing of lead-free solder joints.

His models can be used to predict the reliability and useful life of a lead-free solder joint. Accelerated testing simulates the stresses that are expected to occur over the service life of the product in a short period of time. Additionally, Kregting et al. (2012) models the reliability of lead-free solder joints through virtual design qualification, where accelerated testing of solder joints is simulated with computer models. The Kregting et al. and Lau et al. models predict the reliability of lead-free solder through accelerated testing. Their focus is on projecting how a product performs when lead-free solder is used in the place of tin-lead solder.

In this chapter, the model developed in Chapter 2 will be used to project the cost implications of implementing a lead-free solder control plan on a power supply whose manufacturer has recently changed from using tin-lead solder to lead-free solder. The case study will analyze the system under two sets of conditions: in one situation the power supply is used in desktop computers and in the other situation the power supply is used in a commercial aircraft.

3.1 Lead-Free Control Plan Background

The performance and reliability of electronic parts is of great concern to the aerospace industry, and the problem of transitioning to from tin-lead solder to lead-free solder is particularly difficult for aerospace applications for a number of reasons. First, avionics and other electronic systems in aerospace systems often operate in extreme environments, exposed to temperature extremes, high altitudes, and shocks (Pinsky et al. 2008). Also, unlike consumer electronics that have service lives of months or a few years, aerospace systems are operated for decades (Pinsky). Finally, the consequences of failure in aerospace systems are dire, including loss of life and great financial losses.

Given the high stakes of electronic performance in aerospace systems, the *Aerospace Industries Association* created the *Pb-Free Electronics Risk Management Consortium* (PERM) to provide guidance and leadership to the aerospace industry and respond to the challenges posed by the use of lead-free solder in aerospace and defense applications. As Pinsky states, the goal of the lead-free control plan is to "document processes that assure the Plan owners, their customers, and all other stakeholders that aerospace and high performance high-reliability electronics systems will continue to be reliable, safe, producible, affordable, and supportable" (Pinsky et al. 2008).

A lead-free control plan defines the reliability objectives of a system, outlines all the risks that are threats to achieving those requirements, and defines the processes that will be performed to ensure the stakeholders' reliability requirements are met. In the context of this thesis, the processes of the lead-free control plan are called activities (defined in Section 2.6 of this thesis). In the context of the case study presented in this chapter, the lead-free control plan defines a set of activities that the user may implement with the goal of improving the reliability of the system so that it meets all stakeholders' reliability requirements. Also, some activities may be required by industry standards or law, but the user may have a choice as to the level of rigor that they are performed with and whether to perform other activities that are not required.

The control plan used in this thesis for the case study in this chapter is based on the standards and practices outlined by the PERM. The activities of the case study are detailed in Section 3.7.

3.2 Power Supply Description

We wish to test the applicability of the model developed in Chapter 2 by applying it to a case study that evaluates the value (or lack of value) associated with a control plan for lead-free solder implementation in a power supply. In this case study, we will analyze a power supply from a desktop personal computer. We consider the hypothetical situation that the manufacturer of the computer power supply must, due to new regulation, use lead-free solder instead of tin-lead solder. Changing solder is difficult for the manufacturer because a new solder may affect the reliability of the power supply, and less data exists on the performance of lead-free solder than tin-lead solder.

Specifically, this case study uses a Dell power supply (Model: NPS-250KB) with a variable 100-120V – 9.0 A / 200-240V – 4.5 input and 5V – 22.0A / 12V – 14.0A output. Figure 11 shows the power supply. Figure 12 shows the power supply's components attached to the printed circuit board (PCB) and Figure 13 shows the solder connections, both through hole and surface mount, on the reverse of the PCB.

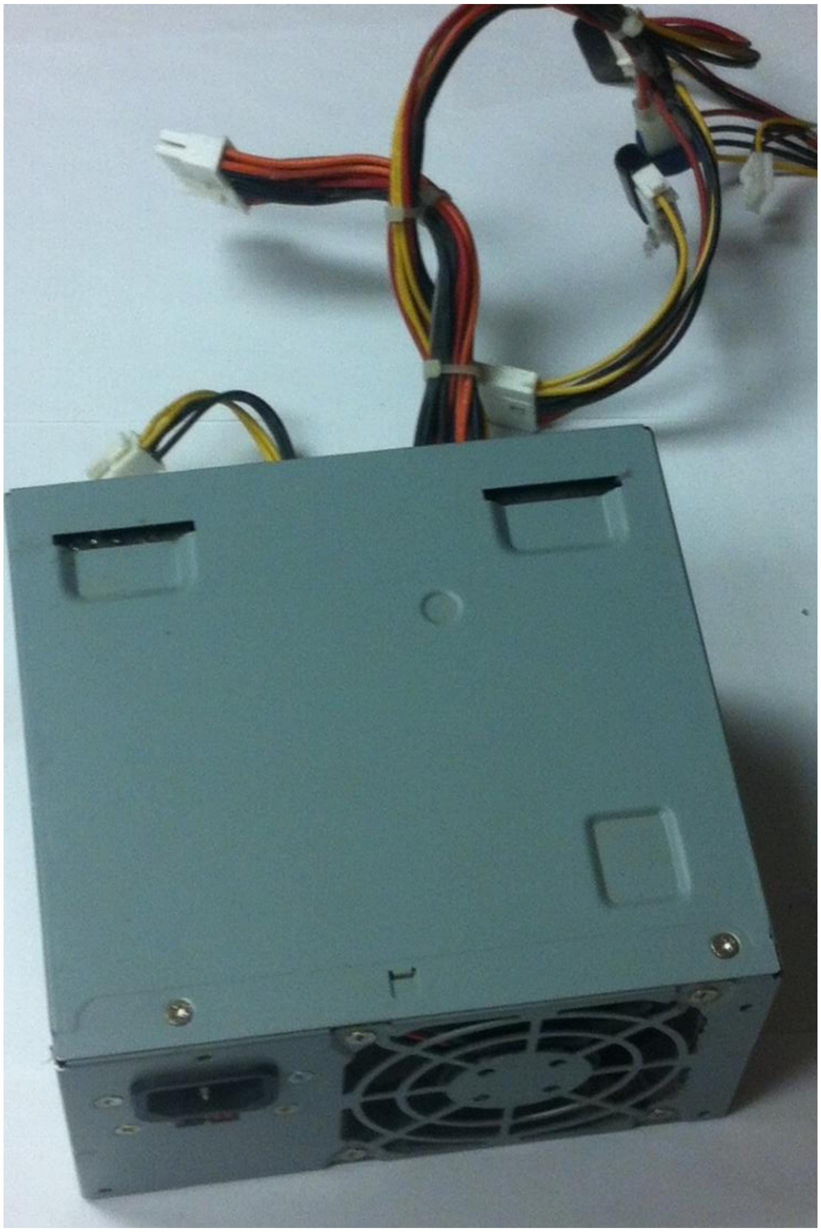


Figure 11: The power supply used in the case study

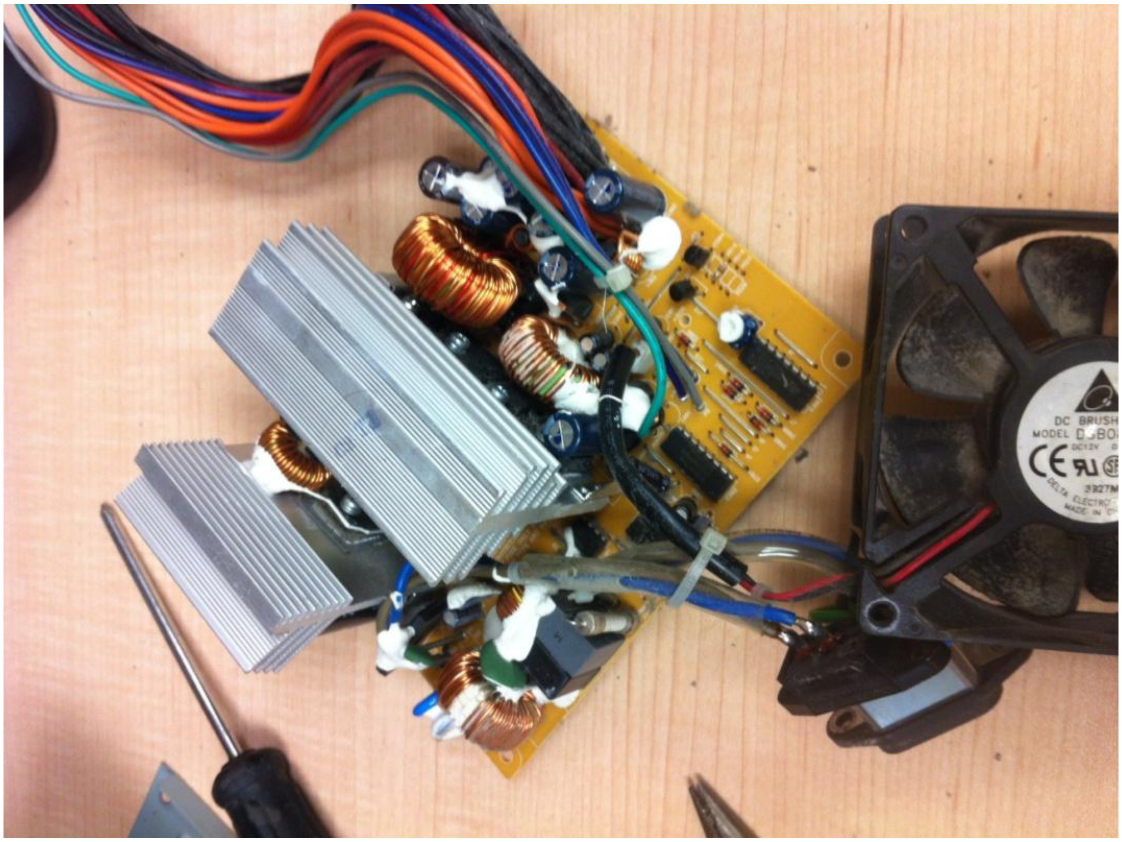


Figure 12: Components on the PCB

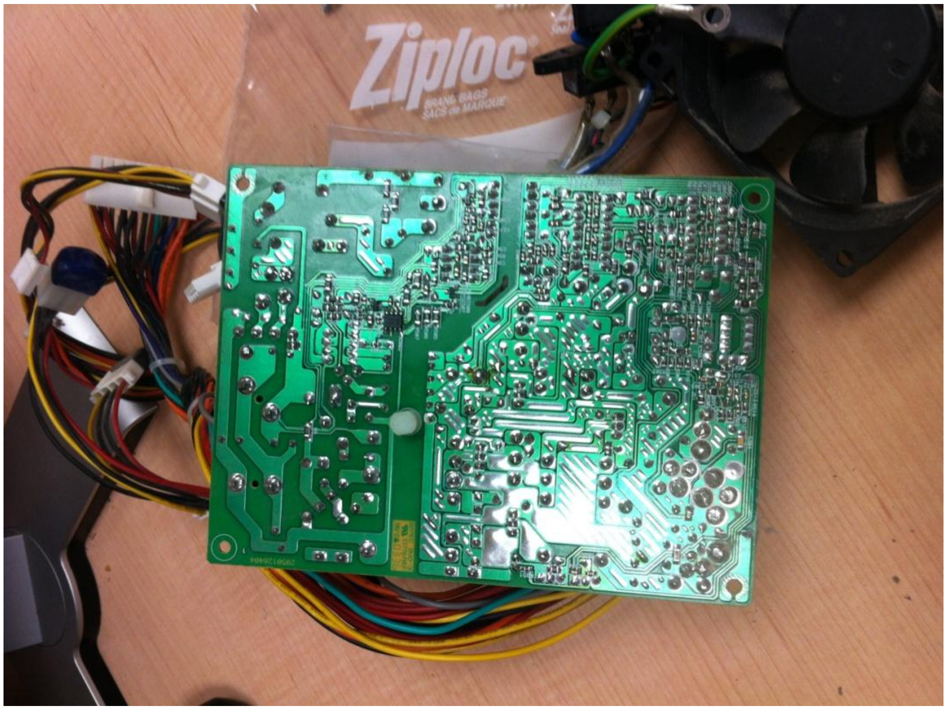


Figure 13: Solder connections on the reverse of the PCB

For a detailed list of solder connections, see Table 10.

To conduct the case study, we must first create a FMMEA for the power supply. The FMMEA used in this case study is based on two existing failure analyses on power supply failure modes, mechanisms, and causes: one on power supply voltage regulations by Matthew et al. (2012) and one on power supply cooling units (fans) by Oh et al. (2010). The analyses in the Matthew et al. and Oh et al. were used to construct a comprehensive FMMEA for the power supply, which is not shown in this thesis.

3.3 Scope of the Lead-free Case Study

Using the FMMEA, the model calculates the projected cost of failure consequences (PCFC) for all of the failures that are expected to occur during the service life of the product (or fleet of products). Additionally, several proposed activities that have the potential to reduce the probability of failures occurring are described (these are the activities in the control plan). If an activity reduces the number of failures, then PCFC will be reduced. Then, various combinations of these activities are tested in the model in an attempt to determine the best combination of control plan activities that fulfills the system owner's reliability and cost requirements. It is important to note that the goal of the case study is to analyze and optimize the lead-free solder control plan activities, not to analyze the decision to convert the power supply to lead-free solder. We assume that the owner has already made the decision to transition to lead-free, or that its transition is required by outside factors.

For this case study, we are interested in analyzing the cost implications of lead-free control plan activities on the power supply. Since we assume our activities only affect lead-free parts, we do not have to consider all failures listed in the comprehensive FMMEA. Instead, we will only consider the failures associated with the solder connections of the parts to the PCB. Table 9categorizes the solder connections on the PCB by type of connection and the parts connected to the PCB.

Table 9: Solder connections on the power supply PCB

Solder Joint	Capacitor	Wires	IC	Resistor

Through Hole-Large	4	16	0	0
Through Hole-Medium	0	3	0	0
Through Hole-Small	24	0	48	36
Surface Mount- 2 Lead	24	0	0	86
Surface Mount- 3 Lead	0	0	0	3
Surface Mount- 8 Lead	0	0	0	1

In the FMMEA, solder connections failures are classified based on the circuit element connected, the size of the connection, and the type of solder connection (through hole or surface mount). For example, in this FMMEA, large through-hole solder joints connecting capacitors are one distinct “part. Three failures modes are associated with each part in the FMMEA, where a part is a set of solder connections with a distinct size, type, and circuit element being connected. Open circuits and intermittent open circuit failure modes are associated with failure cause and mechanism temperature cycling and fatigue, respectively. The short circuit mode is associated with a failure cause of conductive bridge and failure mechanism of fatigue. The difference between an intermittent open circuit and a “non-intermittent” open circuit is that an intermittent open circuit will close after a period of time, and that a “non-intermittent” open circuit stays open until maintenance is performed. In this thesis is it assumed that failures associated with intermittent open circuits are less severe that failures associated with permanent open circuits. The subsection of the FMMEA used for the case study is shown in Table 10:

Table 10: Subsection of the comprehensive FMMEA used in the case study

Failure Number	Number of Parts	Part	Failure Mode	Failure Cause	Failure Mechanism
1	4	PCB- Capacitor Through Hole Solder Joint- Large	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
2	4	PCB- Capacitor Through Hole Solder Joint- Large	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
3	4	PCB- Capacitor Through Hole Solder Joint- Large	Short Circuit	Conductive Bridge	Tin Whisker
4	16	PCB- Wire Through Hole Solder Joint- Large	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
5	16	PCB- Wire Through Hole Solder Joint- Large	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue

6	16	PCB- Wire Through Hole Solder Joint- Large	Short Circuit	Conductive Bridge	Tin Whisker
7	24	PCB- Capacitor Through Hole Solder Joint- Small	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
8	24	Capacitor Through Hole Solder Joint- Small	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
9	24	Capacitor Through Hole Solder Joint- Small	Short Circuit	Conductive Bridge	Tin Whisker
10	22	PCB- Surface Mount Capacitor- 2 Lead Connection	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
11	22	PCB- Surface Mount Capacitor- 2 Lead Connection	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
12	22	PCB- Surface Mount Capacitor- 2 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
13	86	PCB- Surface Mount Resistor- 2 Lead Connection	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue

14	86	PCB- Surface Mount Resistor- 2 Lead Connection	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
15	86	PCB- Surface Mount Resistor- 2 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
16	3	PCB- Surface Mount Resistor- 3 Lead Connection	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
17	3	PCB- Surface Mount Resistor- 3 Lead Connection	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
18	3	PCB- Surface Mount Resistor- 3 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
19	1	PCB- Surface Mount Resistor- 8 Lead Connection	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
20	1	PCB- Surface Mount Resistor- 8 Lead Connection	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
21	1	PCB- Surface Mount Resistor- 8 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker

22	2	PCB-IC- 14 Lead Connection	Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
23	2	PCB-IC- 14 Lead Connection	Intermittent Open Circuit/ Cracked Solder Joint	Temperature Cycling	Fatigue
24	2	PCB-IC- 14 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker

3.4 Case Study Environmental and Operating Conditions, and Consequences of Failure

This case study will analyze the cost implications of implementing a lead-free control plan on the power supply after its manufacturer has recently switched from using leaded solder to lead-free solder for two cases: one where the power supply is used in a desktop computer; and the other where the power supply is used in a commercial aircraft. These cases differ in several aspects. First, the environmental conditions of each are very different. A desktop computer is in an environment that is assumed to have stable temperatures, pressure, and humidity, while in an aircraft these conditions vary greatly. Additionally, we are assuming that the power supply on the aircraft is operating in the unpressurized, non-climate controlled, tail of the aircraft, colloquially (and quite aptly) known as the “hell hole.” The conditions in the hell hole are assumed to be those defined by Das (1999). Das (1999) notes that while the IPC outlines the worst case temperature change for one thermal cycle (one flight) to be 20 degrees C, actual field data shows that temperatures can range up to 40 degrees C in flight.

Also, the power supply may have different service lives and rates of use depending on its application. For this case study, we assume that while a typical commercial aircraft can have an expected service life of 20 years or more, this power supply will only be in use for 5 years, and then it will be replaced. Also, we assume that the power supply is part of a safety critical component of the aircraft, but that a redundant identical power supply exists. Thus if the power supply fails the redundant power supply takes over operation. However, if the failure of the power supply is severe enough to render the power supply non-operational, then the aircraft is not allowed to fly again until corrective action is taken, i.e., both the power supply and its redundant power supply must be operational to fly again. The wait time for corrective action could result in significant financial consequences for the aircraft operator. Alternatively, we assume that when the power supply is used in a PC it has an expected service life of 5 years. When the power supply is used in a desktop computer, it is assumed that it will experience on average 1 temperature cycle per week, as the computer is turned on and off only periodically. When used in an aircraft, we assume the power supply will experience one temperature cycle per flight, and that the aircraft is making an average of 6 flights per operational day, and that it operates 300 days per year. Table 11 summarizes the operational expectations of the power supply when used in both applications.

Secondly, the consequences of failure for a power supply in an aircraft will be far greater than for a power supply in a desktop computer. Note that in the context of this thesis, we consider the consequences of failure in terms of the financial loss to the entity responsible for the performance of the system, such as warranty claims, lawsuits, and loss of potential profits. This entity will incur a financial loss if system failures occur. We are assuming that this is obligated to keep the system operational for a predetermined service life, so if a failure occurs the owner must pay to resolve any consequences resulting from that failure and pay money to repair or replace the system so it can continue to operate until the end of its set service life. This entity could be the operator of the system, or the manufacturer of the system if it is under a warranty that requires the manufacturer to pay for all consequences of failure during the warranty period. In the latter case, the service life of the system would be defined as the warranty period. In Table 11, the use conditions (temperature cycles per year) and service life are shown for both applications of the power supply. For the PC case, we assume the entity responsible for failure costs is the manufacturer, and the PC is under warranty for the service life (five years). In the commercial aircraft case, we assume the entity responsible for failure costs is an airline (the system operator). Table 12 shows the assumed consequences and likelihoods of varying severity and occurrence ratings of failure when the power supply used in a desktop PC and Table 13 shows the assumed consequences and likelihoods of varying severity and occurrence ratings of failure when the power supply is used in a commercial airplane.

Table 11: Comparison of the usage conditions for the application of the power supply in a commercial aircraft and a personal computer.

Power Supply Used In:	PC	Commercial Aircraft
Temperature Cycles	9000	36000
Service Life (Years)	5	20
Temperature Cycles Per Year	1800	1800
Number of Units in Service	100,000	500

Severity of Failure	Failure Event Associated With:	Failure Cost	Occurrence Rating		Expected Number of Failures per product per unit lifetime
1	Minor Nuissance	$10	1	Unlikely	0.0001
2	Repair of Power Supply	$75	2	Remote	0.001
3	Replacement of Power Supply	$150	3	Occasional	0.01
4	Replacement of Power Supply, collateral damage to PC	$750	4	Reasonably Probable	0.1

5	Loss of Entire PC	$1,500	5	Frequent	1

Severity of Failure	Failure Event Associated With:	Failure Cost	Occurrence Rating		Expected Number of Failures per product per unit lifetime
1	Minor Nuissance	$100	1	Unlikely	0.0001
2	Repair of Power Supply	$2,500	2	Remote	0.001
3	Replacement of Power Supply	$5,000	3	Occasional	0.01
4	Repair or Replace, Interrupting Flight Schedule	$25,000	4	Reasonably Probable	0.1
5	Repair or Replace, Jeopardizing Flight Safety	$250,000	5	Frequent	1

In this case study we assume that all repair and replace maintenance actions result in a good-as-new part returning to the soccer. However, this assumption may not be entirely accurate, as repair of solder joints performed by humans can result in less than good-as-new joints, in the case of tin whiskers or open circuits.

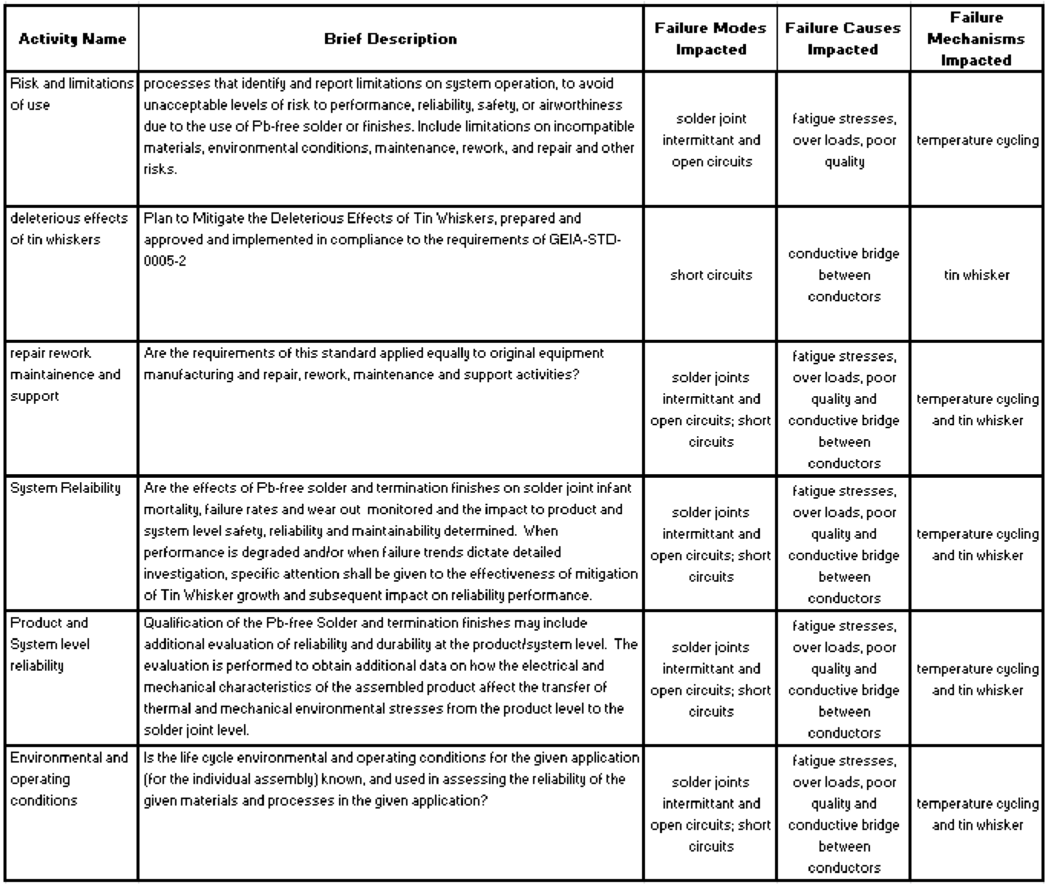
Also, the minor nuisance failure event could be a no fault found failure event. This case study assumes that the financial consequences of a no fault found event (severity level one) do not change if multiple no fault found events occur on the same board. But, some companies in industry have policies limiting boards to three no fault found events. These companies require that if a board has three no fault found events, and the underlying cause is discovered, the board is thrown out. Adapting these policies to the model would mean that a third severity level one event on a particular board would actually be a severity level three event; however that case is not modeled in this case study.

3.5 Lead–Free Control Plan Activities

The purpose of a lead-free control plan is to ensure that a product or system that transitions from tin-lead solder to lead-free solder will meet its reliability requirements when using lead-free solder. The lead-free control plan is a set of activities that a manufacturer can choose to perform to ensure reliability requirements are met. Performing activities qualifies the product or its manufacturing processes. Activities are paid for before they are performed, so the manufacturer pays money prior to making the product with the aim of reducing failure costs that will be incurred over the product service life.

There are several activities that the user may choose to implement for this case study. The activities can be applied to both applications of the power supply (in a desktop computer or commercial aircraft). Table 14 shows the six activities the user can choose to perform in the case study.

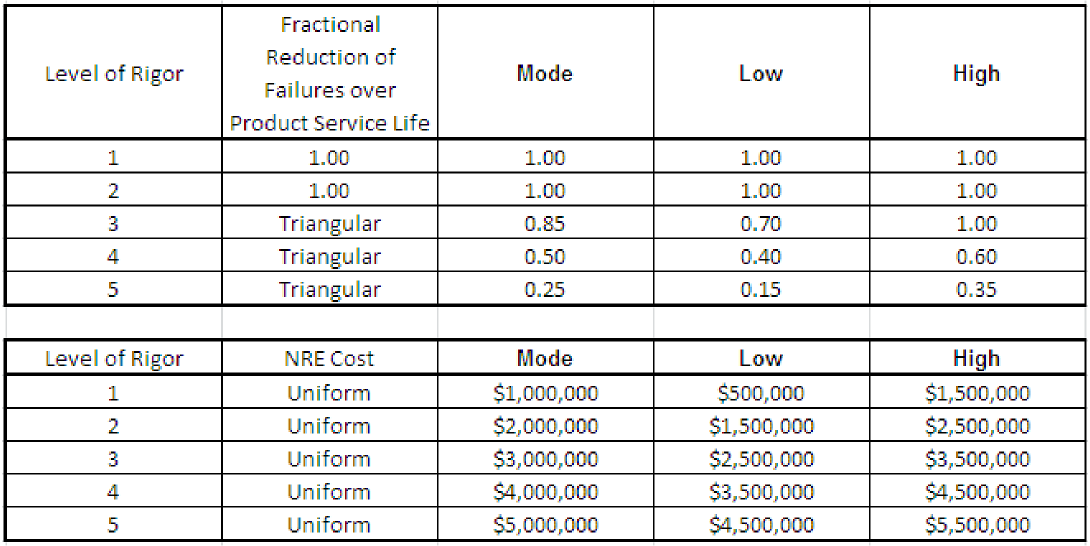
Table 12: Lead-free control plan activities



Activity Name	Brief Description	Failure Modes Impacted	Failure Causes Impacted	Failure Mechanisms Impacted
Risk and limitations of use	processes that identify and report limitations on system operation, to avoid unacceptable levels of risk to performance, reliability, safety, or airworthiness due to the use of Pb-free solder or finishes. Include limitations on incompatible materials, environmental conditions, maintenance, rework, and repair and other risks.	solder joint intermittant and open circuits	fatigue stresses, over loads, poor quality	temperature cycling
deleterious effects of tin whiskers	Plan to Mitigate the Deleterious Effects of Tin Whiskers, prepared and approved and implemented in compliance to the requirements of GEIA-STD-0005-2	short circuits	conductive bridge between conductors	tin whisker
repair rework maintainence and support	Are the requirements of this standard applied equally to original equipment manufacturing and repair, rework, maintenance and support activities?	solder joints intermittant and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	temperature cycling and tin whisker
System Relaibility	Are the effects of Pb-free solder and termination finishes on solder joint infant mortality, failure rates and wear out monitored and the impact to product and system level safety, reliability and maintainability determined. When performance is degraded and/or when failure trends dictate detailed investigation, specific attention shall be given to the effectiveness of mitigation of Tin Whisker growth and subsequent impact on reliability performance.	solder joints intermittant and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	temperature cycling and tin whisker
Product and System level reliability	Qualification of the Pb-free Solder and termination finishes may include additional evaluation of reliability and durability at the product/system level. The evaluation is performed to obtain additional data on how the electrical and mechanical characteristics of the assembled product affect the transfer of thermal and mechanical environmental stresses from the product level to the solder joint level.	solder joints intermittant and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	temperature cycling and tin whisker
Environmental and operating conditions	Is the life cycle environmental and operating conditions for the given application (for the individual assembly) known, and used in assessing the reliability of the given materials and processes in the given application?	solder joints intermittant and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	temperature cycling and tin whisker

Additionally the user has the choice to perform or not perform each activity in the control plan. Additionally, each activity can be performed at various levels of rigor. For example, the cost and benefit details for the activity "Risk and limitations of use" are shown in Table 15.

Table 13: Cost and benefit data for various levels of rigor of performing the activity “Risk and limitations of use” (NRE = non-recurring)



Level of Rigor	Fractional Reduction of Failures over Product Service Life	Mode	Low	High
1	1.00	1.00	1.00	1.00
2	1.00	1.00	1.00	1.00
3	Triangular	0.85	0.70	1.00
4	Triangular	0.50	0.40	0.60
5	Triangular	0.25	0.15	0.35

Level of Rigor	NRE Cost	Mode	Low	High
1	Uniform	$1,000,000	$500,000	$1,500,000
2	Uniform	$2,000,000	$1,500,000	$2,500,000
3	Uniform	$3,000,000	$2,500,000	$3,500,000
4	Uniform	$4,000,000	$3,500,000	$4,500,000
5	Uniform	$5,000,000	$4,500,000	$5,500,000

3.6 Case Study Results

In this section the model is applied to the power supply, first where the power supply is used in a PC, and second where the power supply is used in an aircraft. For both scenarios we assume that the consequences of failure of the power supply are given in Tables 11 and 12, and that all activities from the lead-free control plan are performed. Every solder joint on the circuit board of the power supply is assumed to use SAC305 solder is modeled with a Weibull distribution. The β parameters used in the Weibull distributions are based off of the testing done by George et al. (2012) and Wang (2011), however, no good data could be found on the characteristic life (η) of SAC305 solder for the conditions in the case study. Each activity is performed at a level of rigor of 3, and we have assumed that the cost and benefit of each activity performed in this case study is the same as the activity “Risk and limitations of use” which is described in Table 15. The tin whisker failures were modeled based on the work published by Rifat (2008). Each application of the power supply was run for 100 trials. Each trial calculates the initial PCFC by sampling the Weibull distributions for each part.

In this thesis, each solder joint on the power supply represents a socket (a place where a part goes). Each socket must complete the number of cycles as defined by the service life. If a solder joint does not last for its service life then it is assumed that corrective action is taken (repair or replace) and the socket samples the Weibull again until the cumulative lives (in cycles) of the parts in the socket are greater than or equal to the service life (also in cycles). Then each trial calculates: an investment cost (the cost of performing activities) by sampling the cost distribution defining the cost of performing the activity at the severity level chosen, a return (the reduction in PCFC after performing activities) by sampling the distribution defining the fractional reduction in failures for each activity performed and applying the factional reduction in failures to the failures in the FMMEA that the activity affects, and an ROI. Calculations are described in detail in Chapter 2 of this thesis. Thus, for each trial, the initial PCFC, investment cost, and return could be different because the parameters that determine them are defined as distributions that are sampled for each trial.

3.6.1 Desktop Computer Case Study

In this section, the model is run in the case of applying the lead free control plan to a power supply used in a desktop computer. Because the characteristic life of SAC305 solder was unknown, the model was run three times with three different values of the solder characteristic life: 25,000, 50,000, and 75,000 cycles. The results of the case study are shown in Figures 14 to 19, where the blue lines represent the system before the lead-free control plan activities are performed, and the red lines represent the system after the lead-free control plan activities are performed. Note that while 100 trials were performed, Figures 14, 66, and 18 only show the graphical results of the first 15 trials. Figures 15, 17, and 19 show a histogram of the 100 ROIs that were calculated for the 100 trials.

The actual numbers generated for the first trial of the PC case where η = 50,000 cycles where as follows: PCFC (for a population of 100,000 PCs) before activities are performed: $6,500,000, cost of performing activities: $17,454,122, PCFC after activities are performed: $2,804,656, reduction in PCFC due to performing activities: $3,695,344, ROI: -79%.

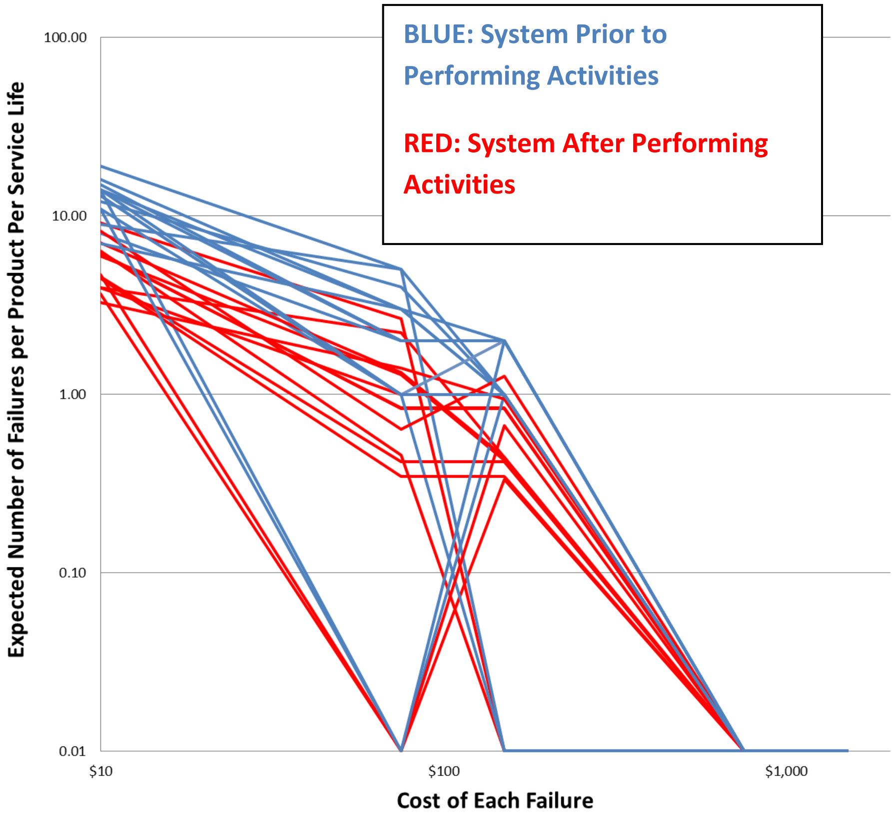


Figure 14: Results for the PC case where solder characteristic life (η) = 25,000 cycles

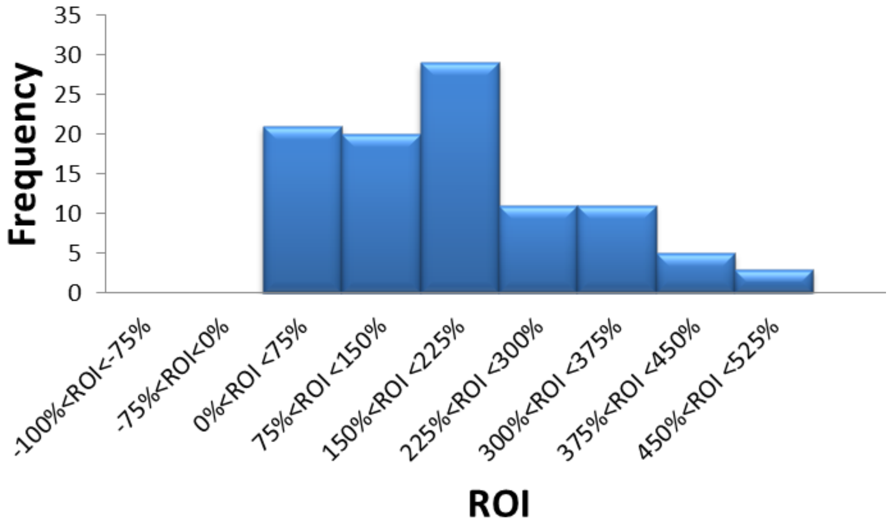


Figure 15: Histogram of ROIs, η = 25,000 cycles

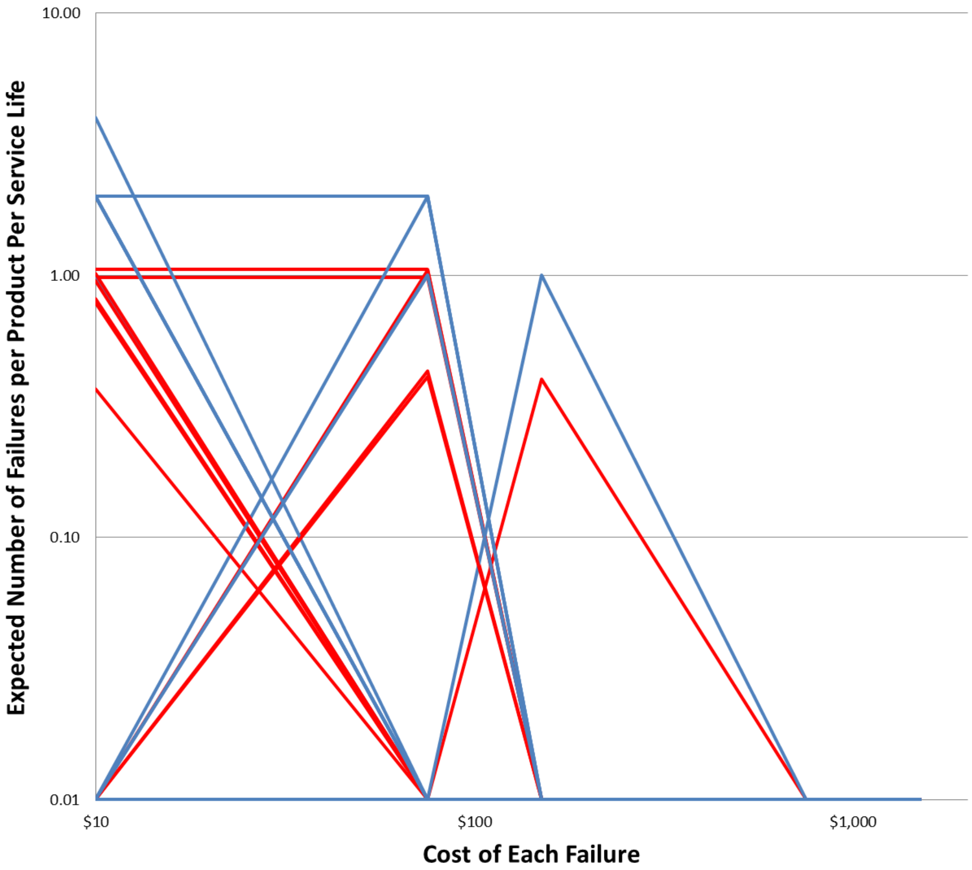


Figure 16: Results for the PC case where η = 50,000 cycles

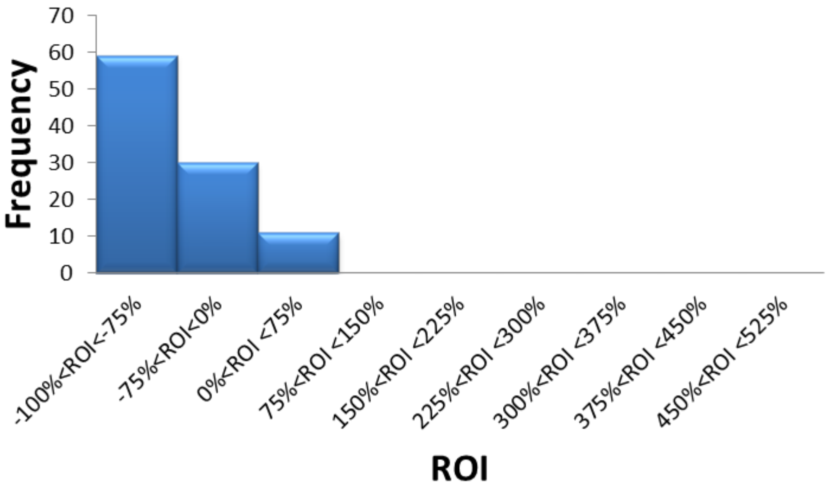


Figure 17: Histogram of ROIs, η = 50,000 cycles

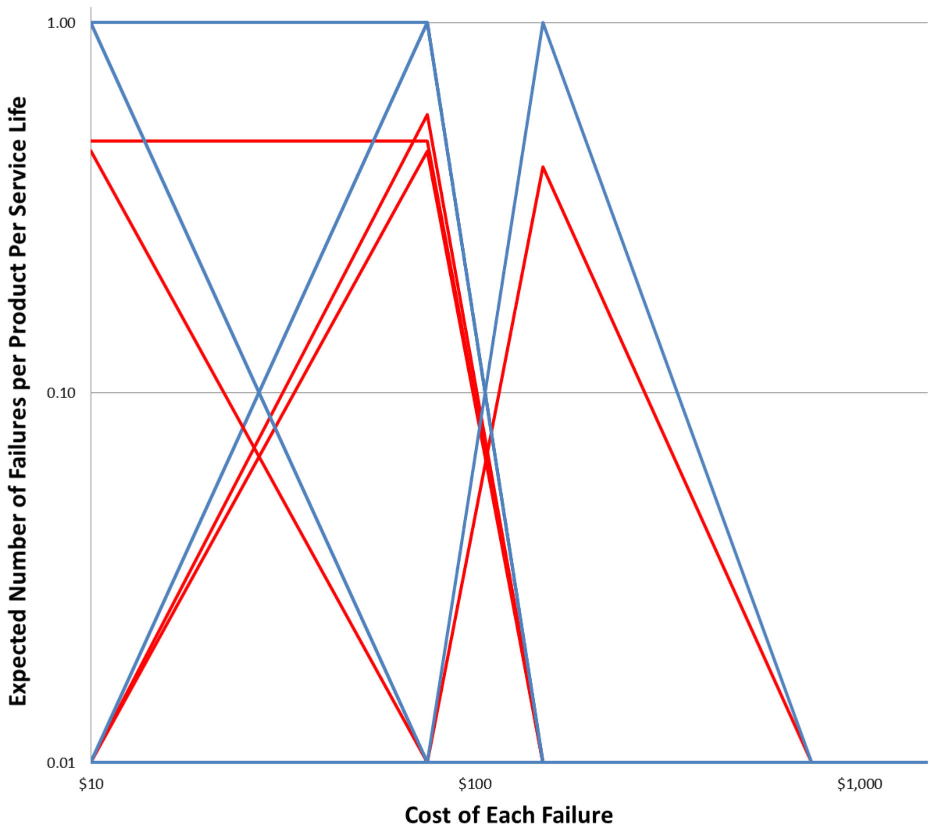


Figure 18: Results for the PC case where η = 75,000 cycles

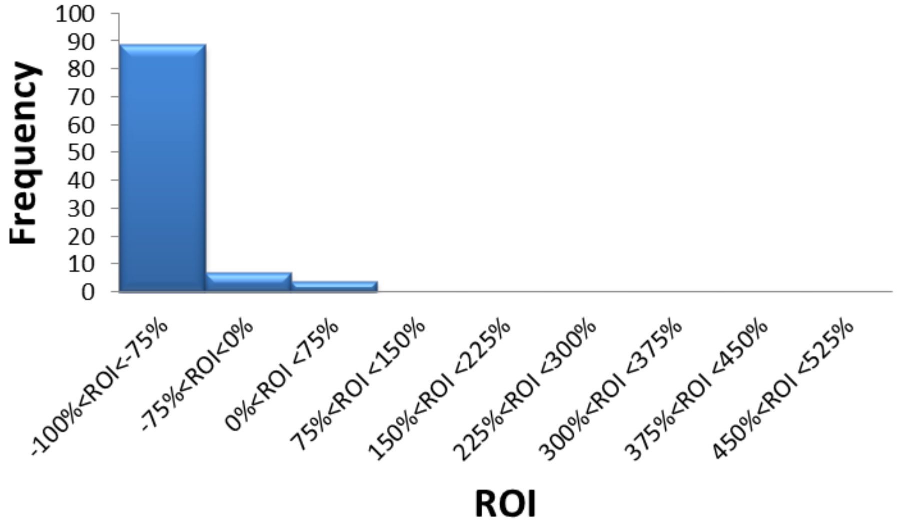


Figure 19: Histogram of ROIs, η = 75,000 cycles

In two of the cases (η = 75,000 and 50,000) the median ROI is negative, because the cost of performing activities is so high that it is greater than the benefit of performing activities in of 90% of the trials. But, when $\eta = 25{,}000$, the initial PCFC is so great that paying for activities to reduce it is cost effective.

3.6.2 Commercial Aircraft Case Study

Next we perform the case study again for a fleet of commercial aircraft. All parameters are the same in this case study as for the PC, except that the PCFC associated with each severity level of failure is much greater because the power supply is being used in an airplane, which is a safety critical system, and the service life of the aircraft is 20 years. As in the PC case study, the study is run three times for varying values of the characteristic life of the solder. Figures 20 to 25 show the results.

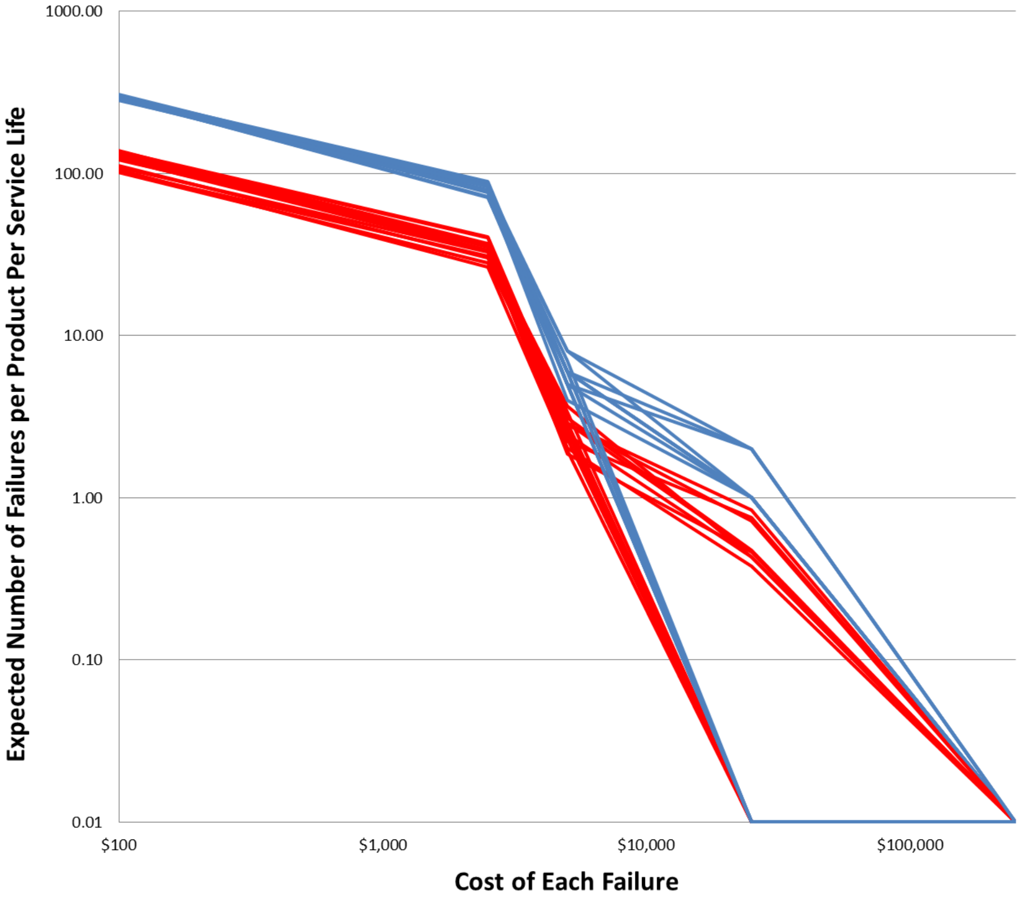


Figure 20: Results for the commercial aircraft case where η = 25,000 cycles

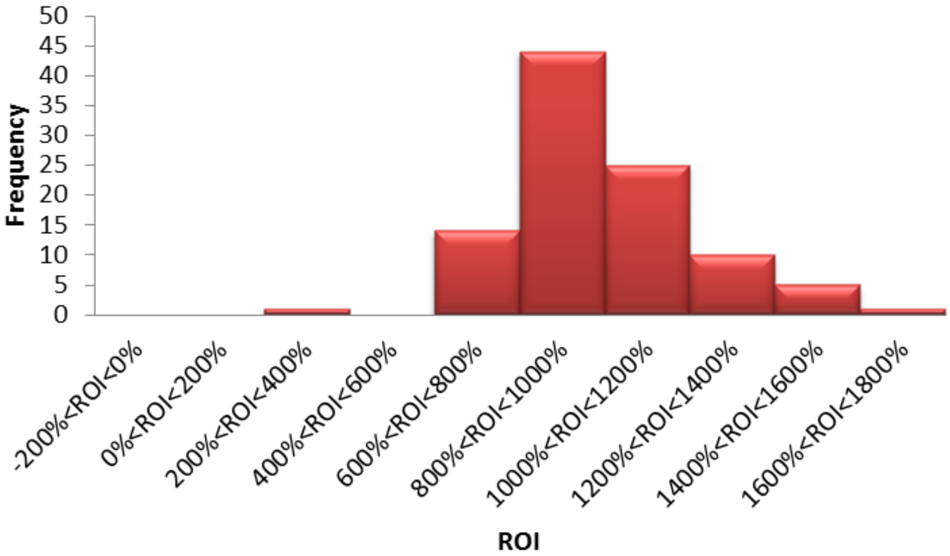


Figure 21: Histogram of ROIs, η = 25,000 cycles

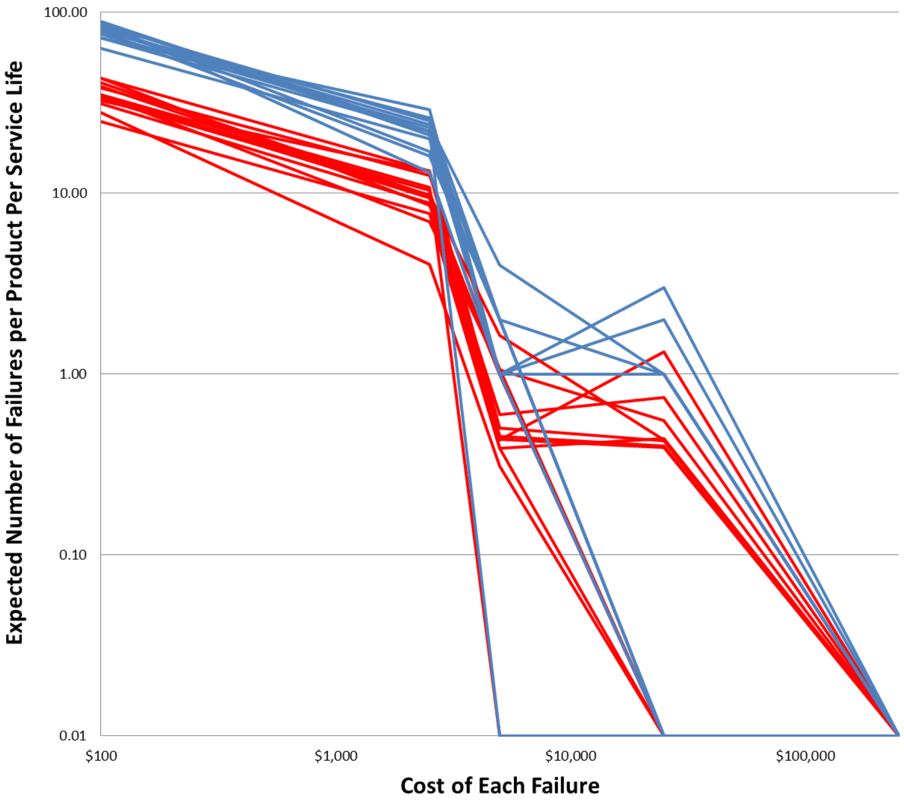


Figure 22: Results for the commercial aircraft case where η =50,000 cycles

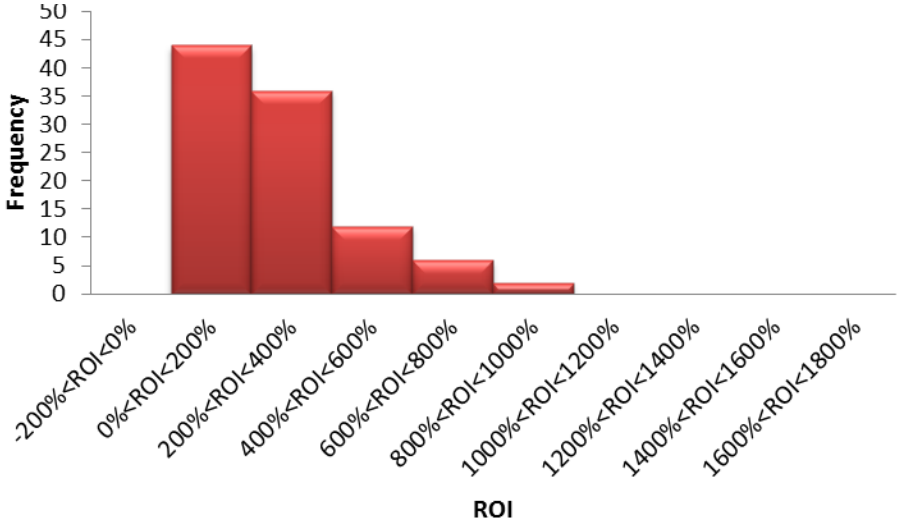


Figure 23: Histogram of ROIs, η = 50,000 cycles

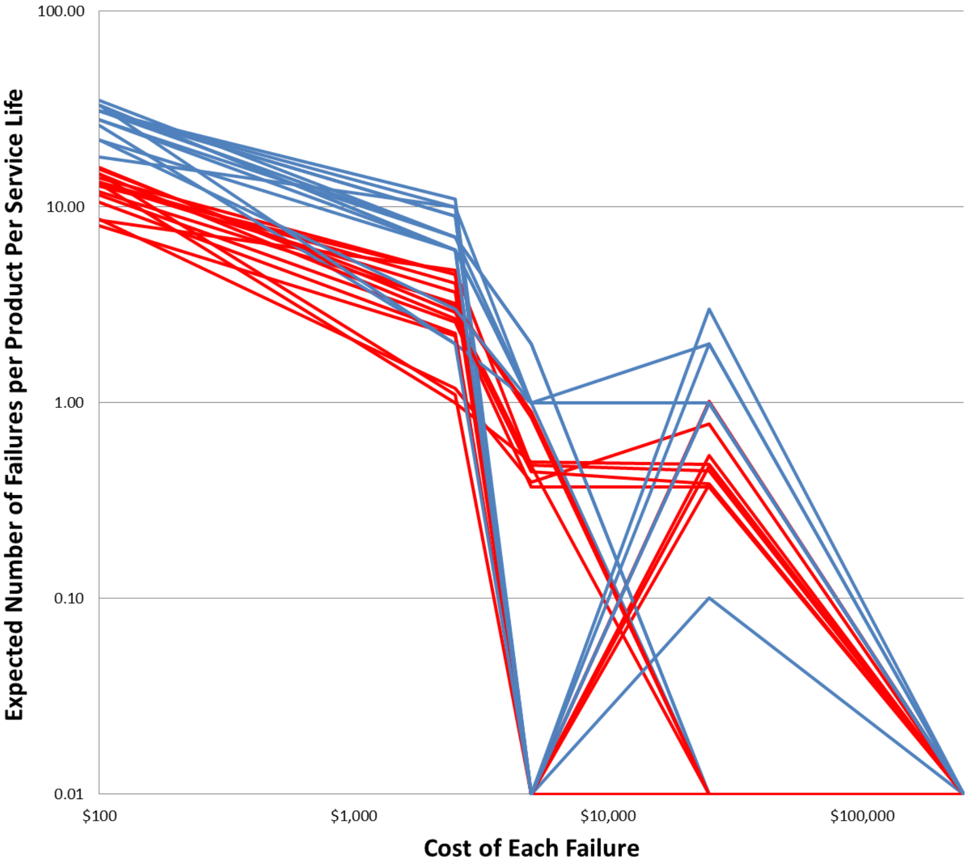


Figure 24: Results for the commercial aircraft case where η =75,000 cycles

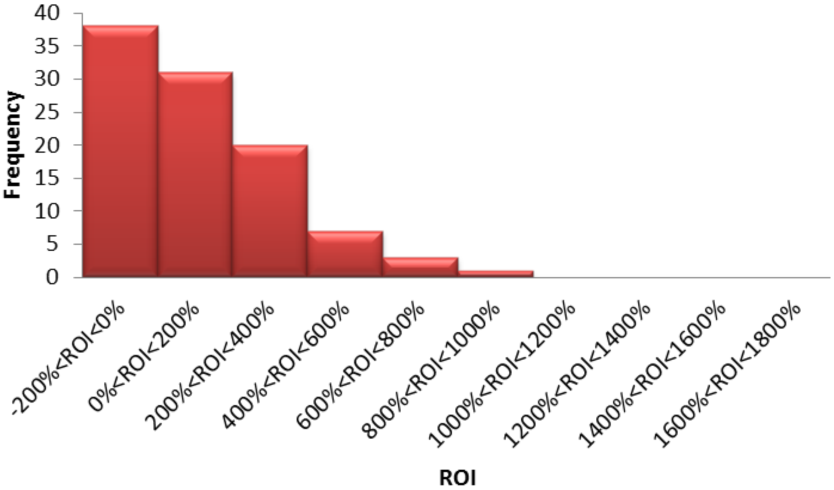
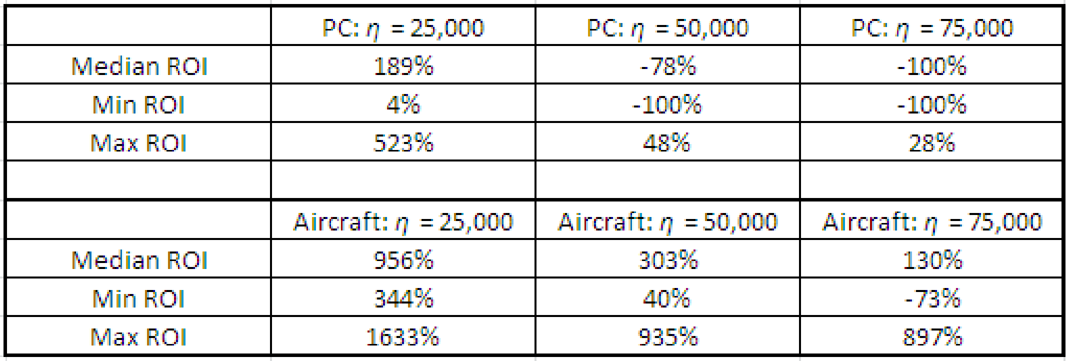


Figure 25: Histogram of ROIs, η = 75,000 cycles

3.7 Discussion

Table 16 shows the minimum, median, and maximum values of ROI for each of the 6 runs of the model.

Table 14: ROI Values



	PC: η = 25,000	PC: η = 50,000	PC: η = 75,000
Median ROI	189%	-78%	-100%
Min ROI	4%	-100%	-100%
Max ROI	523%	48%	28%
	Aircraft: η = 25,000	Aircraft: η = 50,000	Aircraft: η = 75,000
Median ROI	956%	303%	130%
Min ROI	344%	40%	-73%
Max ROI	1633%	935%	897%

For this example, the model shows that performing activities provides more value in the commercial aircraft scenario than the PC scenario. Performing activities is only valid for the PC scenario when the solder has the lowest value of η. When the power supply is used in an aircraft, there is a good case for performing activities in all three scenarios, but when η = 75,000, there is a chance that performing activities will result in a negative ROI.

3.8 Other Scenarios

Now we change other variables to test the model. In each of the following scenarios, model is run on the commercial aircraft scenario with η = 50,000 cycles.

3.8.1 Performing Activities at the Highest Level of Rigor

In the six previous cases, all activities were performed at the 3rd level of rigor but for this simulation we perform them at rigor level 5. The results are shown in Figures 26 and 27.

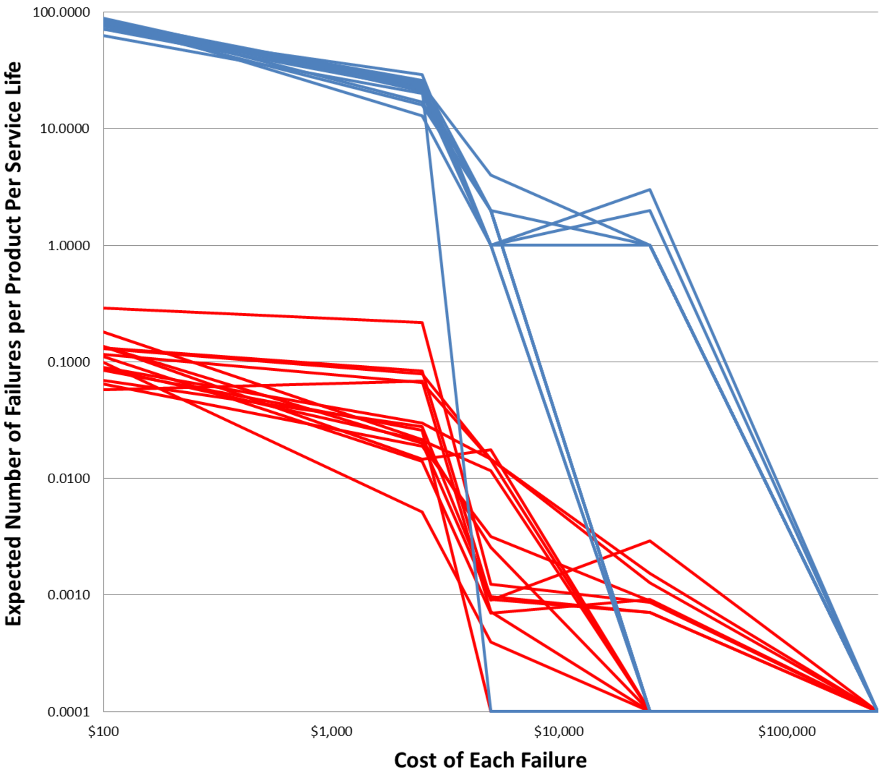


Figure 26: Results for Commercial Aircraft case where *η* =50,000 cycles, activities performed at the highest level of rigor

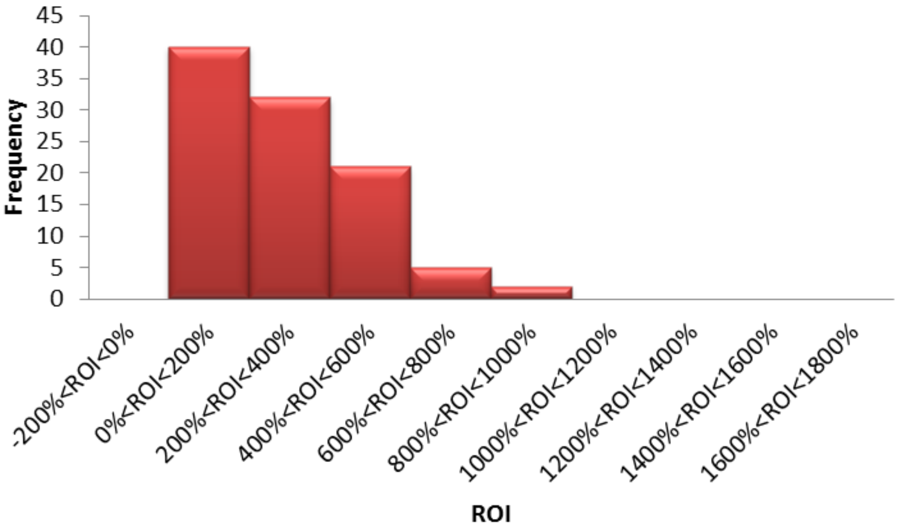


Figure 27: Histogram of ROIs, η = 50,000 cycles, activities performed at the highest level of rigor

The median ROI when all activities we performed at level of rigor 3 is 239% and the median ROI when activities are performed at level of rigor 5 is 265%. There is not much change in ROI because the additional benefits of performing activities at a higher level of rigor cost more to attain.

3.8.2 Activities are not Independent

In every previous case, we have assumed that activities are independent, implying that if multiple activities that affect the same mode, mechanism, cause, or part are performed, the full benefit of each activity is received. Now we assume that performing multiple activities reduces the benefit of performing other activities that affect the same mode, mechanism, cause, or part. In this scenario, we assume that the user performs all activities (because he or she is required to do so by law or regulation), but after performing one activity that affects a particular mode, mechanism, cause, or part, performing additional activities has no effect on that mode, mechanism, cause, or part. Two simulations were run, one with activities performed at the 3rd level of rigor and the other with activities performed at the 5th level of rigor. Figure 28 through 31 show the results.

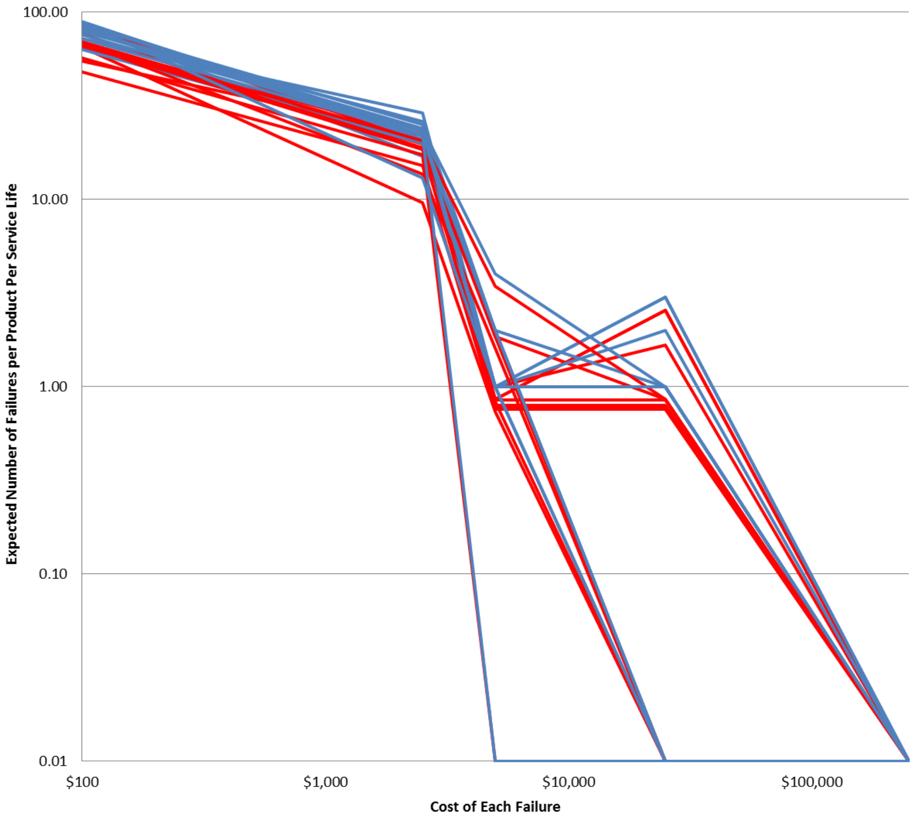


Figure 28: Results for Commercial Aircraft case where η =50,000 cycles, activities performed at level of rigor 3, activities are not independent

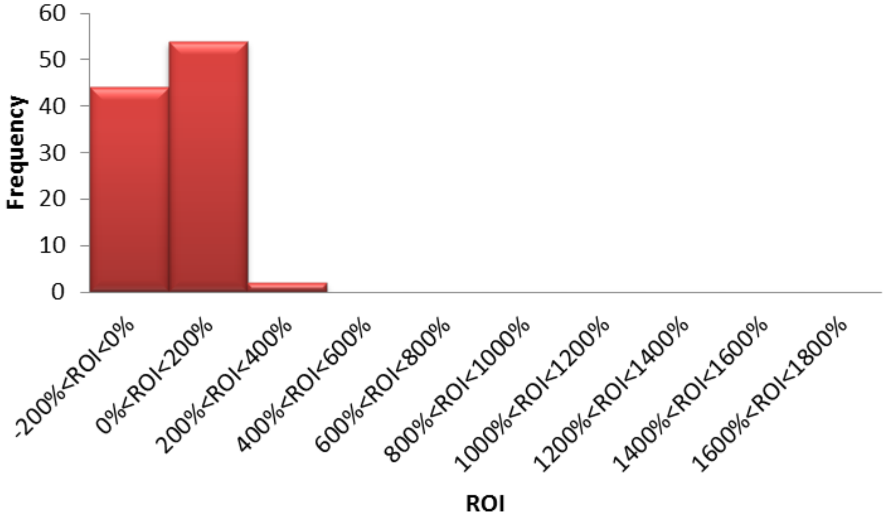


Figure 29: Histogram of ROIs, η = 50,000 cycles, activities performed at level of rigor 3, activities are not independent

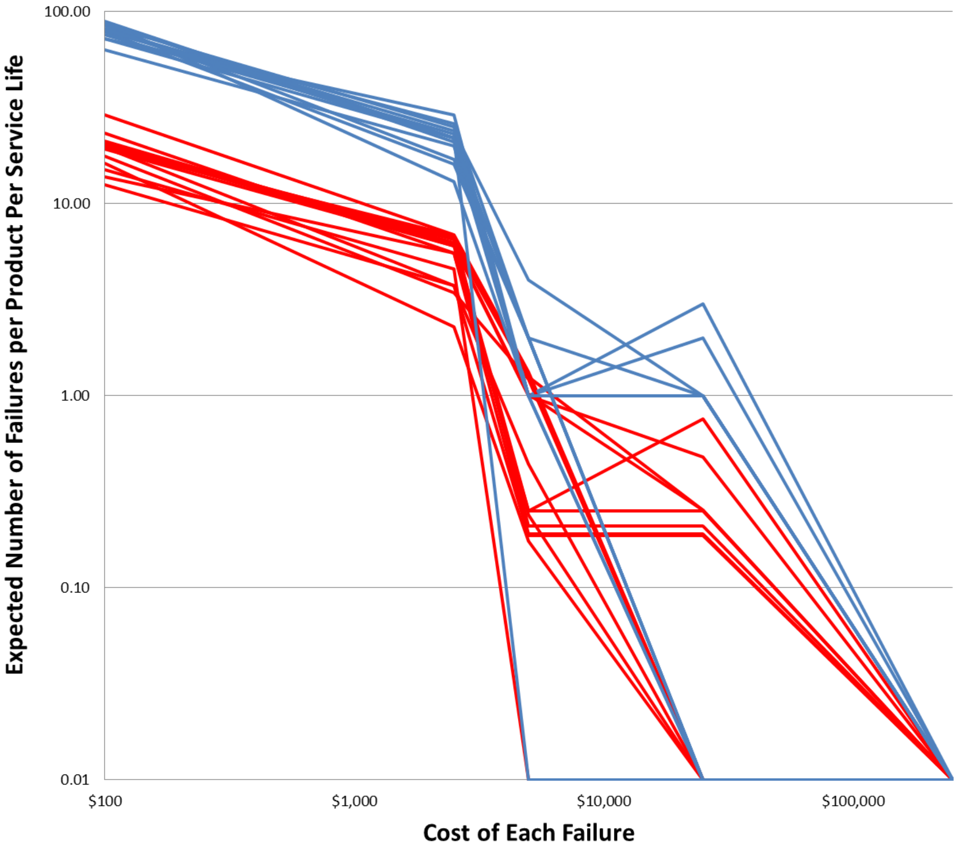


Figure 30: Results for the commercial aircraft case where η =50,000 cycles, activities performed at the highest level of rigor, activities are not independent

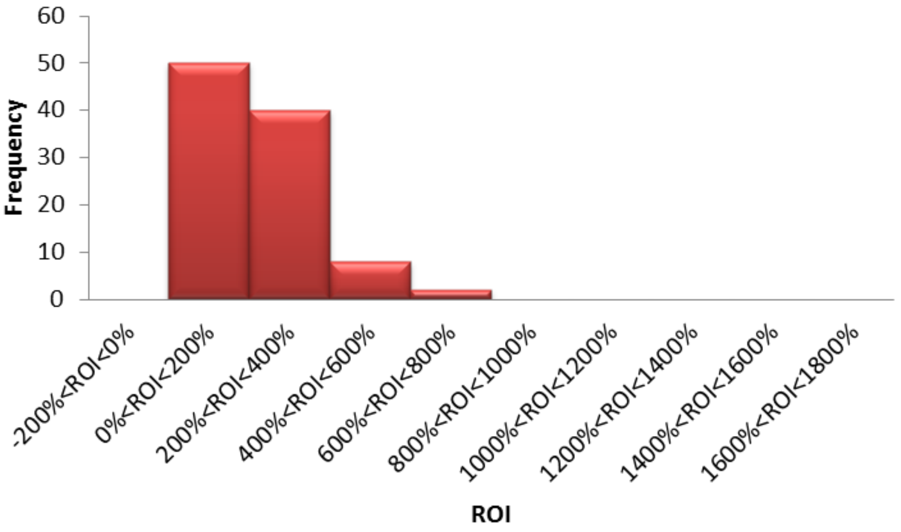


Figure 31: Histogram of ROIs, η = 50,000 cycles, activities performed at the highest level of rigor, activities are not independent

The median ROI when activities are not independent and performed at level of rigor 3 is 4%, and when activities are performed at level of rigor 5 is 175%. Clearly, when activities are not independent, their effectiveness is reduced.

3.9 Conclusions

The case studies presented in this chapter are meant to show the applicability and potential value of the model. They are not meant to create any real world conclusions, as some of the values in the studies are best estimates. But, the case studies show that if a person had reliable data on a system and potential activities, he or she could draw powerful conclusions.

Also, the case studies show the flexibility of the model. It can handle cases where activities are assumed to be independent or not independent of each other. The model can also account for uncertainty in the number of failures to occur over the service life of a product, the cost of performing activities, and the effectiveness of activities. The model uses Monte Carlo techniques to sample the uncertainties over a set of trials and give a range of calculated ROI values.

Chapter 4: Summary, Contributions, and Future Work

4.1 Summary

Adoption and insertion of new technologies and processes into systems is inherently risky. An assessment of the cost of risk may be a necessary part of planning or building a business case to change a system. A cost model that forecasts the cost of risk associated with inserting new technology into a system has been developed. The model projects the cost of inserting new processes, projects the impact of the processes on the cost of risk for the system, and performs a cost-benefit analysis on the adoption of proposed new processes. The projected cost of failure consequences (PCFC) is defined as the cost of all failure events (of varying severity) that are expected to occur over the service life of the system. The PCFC is uncertain, and the potential positive impact of adopting new technologies into the system is to reduce the cost of risk and/or reduce its uncertainty.

A case study that assesses the adoption of a lead-free solder control plan (required by customers) into systems that previously used tin-lead solder has been performed. The case study analyzed the application of the model for two applications: a personal computer (PC) and commercial aircraft. This case study was performed to show that if one had accurate data on the PCFC for a system, the cost of performing various activities, and the benefit of performing the same activities, a judgment could be made, with a quantifiable level of certainty, as to if performing some or all of the activities will be cost-effective. In the case study performed for this thesis, performing activities was far more cost effective when the power supply was used in a commercial aircraft than when used in a PC, because the power supply had a greater service life requirement and higher financial consequences of failure when used in an aircraft. The power supply is projected to fail more often over its service life in an aircraft and the entities responsible for the performance of the power supply incur more cost when the power supply fails, hence there is more benefit to spending money to reduce the expected number of failures.

4.2 Contributions

This thesis developed a model that calculates the projected cost of failure consequences for a system (PCFC). The model also calculates the cost of performing various activities that have the potential to reduce the PCFC, and a return on investment for performing activities. The model links reliability and cost of failure events, and is capable of handling uncertainty in both. Although previous models use severity of failure and likelihood of failure to forecast a cost of quality, risk, failure, or reliability, the model in this thesis not only calculates a cost of failure (defined as PCFC in this thesis), it calculates the reduction in the PCFC when activities are performed and an ROI for performing activities. The model can handle activities performed at various levels of rigor.

The model was used in a case study to assess the financial consequences of performing various activities associated with a lead-free control plan. This model develops a framework that allows the assessment of the cost impact of implementing a lead-free control plan. This thesis provides the first ability to determine the application-specific cost-effectiveness of performing the activities in a lead-free control plan. It can be used to run studies to provide justification for performing or not performing activities in a lead-free control plan.

4.3 Future Work

The interaction between activities needs to be considered and modeled in more depth. The current model assumes that activities are completely independent, that is performing one activity does not affect the benefit associated with performing another. But, this may not be the case, since multiple activities may impact the same failure mechanism. The architecture of the model can accommodate narrowly defining the application of activities to specific parts, specific modes, specific mechanisms, and/or specific parts; however, the model can only assume either the best case, independence of activity impacts, or the worst case, once one activity is performed on a specific mode, mechanism, or cause of failure for a specific part performing additional activities that affect the same mode, mechanism, or cause on the part results in no additional benefit.

Redundancy in systems needs to be accommodated. In the aircraft case study in this thesis, the power supply is assumed to be redundant with another identical power supply, and if the power supply being modeled fails the other power supply immediately takes over. We model various failure events where the power supply is repaired or replaced during scheduled maintenance, and we also model failures that are so severe that aircraft cannot take-off because the power supply needs to be replaced before scheduled maintenance, as there need to be two operational power supplies on the aircraft for it to fly. However, we do not model a situation where one power supply fails, the other kicks in, and then the redundant power supply also fails in the same flight. This is a situation that has very low probability, but one that should be considered if all potential failure events were to be modeled. This could be modeled by a discrete event simulator that models every flight an airplane takes over its service life and checks if the second redundant power supply fails after it takes over.

Further work needs to be done on modeling the solder joints on the board under real usage conditions. As of now, the Weibull parameters are estimates based on existing studies conducted under accelerated testing conditions, however, one could use calcePWA to model the parts on the board under actual usage conditions. Using calcePWA will give us failure data specific to the circuit board, and under actual application-specific usage conditions.

Additional work needs to be performed to verify the model. The case study presented in this thesis shows the applicability of the model, but verification requires further studies. One way to verify the model would be to perform a case study on technology that was implemented into a system and saved money by reducing failure consequences in the past. This would have to be a real-life situation from industry where the results are already known. The model could be run with numbers from the past technology insertion problem, and the model would be verified if it reaches the same conclusion as the real-life scenario. To do this, one would run the model in the hypothetical scenario before technology was inserted, and then see if its projections matched what actually happened.

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