Assessing the value of a lead-free solder control plan using cost-based FMEA

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ABSTRACT

While the transition to lead-free electronics, which began nearly a decade ago, is complete for most commercial products, many safety, mission and infrastructure critical systems that were originally exempt from RoHS and WEEE are only now transitioning. For these types of products qualification is very expensive and the consequences of failure can be catastrophic, therefore carefully engineered control plans are needed when technology or process changes are required. A control plan is a set of activities that a manufacturer can choose or be required to perform to ensure product performance. This paper uses cost-based FMEA to determine the projected cost of failure consequence for a technology insertion control plan for the adoption of lead-free solder for the assembly of electronic systems in critical applications that previously used tin-lead solder. A case study of the lead-free implementation of a power supply demonstrates the return on investment of the control plan for the same product under to different risk scenarios.

1. **Introduction**

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. The environmental and technological issues associated with using lead-free solder in electronic assemblies are discussed elsewhere, e.g., [1,2], and will not be addressed here, but as a result of RoHS and WEEE, product developers must qualify the products (and processes) that they use to replace tin-lead solder with lead-free solder. Changing solder may affect the reliability of a product, and less data exists on the performance of lead-free solder than tin-lead solder.

The performance and reliability of electronic parts is of great concern in many safety-critical applications such as 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 applications often operate in extreme environments, exposed to temperature extremes, high altitudes, vibration and mechanical shock [3]. Also, unlike consumer electronics that have service lives of months or a few years, aerospace systems are operated for decades [3]. Finally, the consequences of failure in aerospace systems are potentially dire, including loss of life and large financial losses.

Given the high stakes of electronic performance in aerospace systems, the *Aerospace Industries Association* created the *Pb-Free Electronics Risk Management* (PERM) *Consortium* 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. One of the PERM Consortium's contributions has been the creation of a performance standard for what a control plan for lead-free solder must include [4]. According to the PERM standard, a lead-free control plan must address, the reliability objectives of a system, outline all the risks that are threats to achieving those requirements, and define the processes that will be performed to ensure the stakeholders' reliability requirements are met. In the context of the study presented in this paper, 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, the customer or the law, but the user may have a choice as to the level of rigor at which they are performed and whether to perform other activities that are not required.

While many qualitative discussions of the cost impacts of lead-free electronics exist, e.g., [5,6], only a few quantitative models have appeared. Palesko [7] analyzed the cost differences between process flows for assembling tin-lead and lead-free electronics. Sandborn and Jafreen [8] develop a cost model for assessing the cost ramifications on an organization of transitioning from tin-lead to lead-free parts. Neither [7] nor [8] address qualification or risk control activities, or the impact of these activities on the cost of a system implemented with lead-free solder. This

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paper describes a model that analyzes the risk and cost implications, good or bad, of adopting activities in the risk control plan for lead-free solder. We are not addressing the tradeoffs associated with conversion from tin-lead to lead-free solder (the models in [7] and [8] can be used for this) – we implicitly assume that a conversion decision has already been made or mandated. The purpose of the analysis described in this paper is to quantify the ramifications of the conversion and establish the value of activities designed to mitigate the conversion risks. We also wish to understand how the cost-effectiveness of adopting lead-free solder changes when the application (i.e., risk environment) changes; although application changes don't necessarily change the consequence of failure, for the particular applications considered in this paper the application changes the consequences of failure significantly.

Section 2 of this paper describes the technology insertion model used to assess the cost of risk of using lead-free solder in systems. Section 3 applies the cost of risk model to a power supply implemented in two different risk scenarios and demonstrates that the optimum control plan differs depending on the usage scenario. Finally, Section 4 discusses the results and suggests analysis extensions.

2. **Technology insertion cost of risk model**

2.1 Review of relevant literature

Barringer [9] defines the cost of reliability as those costs that are used to keep the system free from failure. Models that estimate the cost of reliability based on Barringer's definition include [10,11]. Models based on the risk of failure where failures are ranked based on severity and likelihood of occurrence have also been developed. Hauge and Johnston [12] define risk as "the product of the severity of a failure and the probability of that failure's occurrence". In [12], the severity and occurrence ratings are multiplied together to give a total magnitude of the risk due to the failure. Perera and Holsomback [13] describe a NASA risk management approach, which prioritizes risks based on likelihood and severity, with equal weight given to both factors. Perera and Holsomback identified risks 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". Sun et al. [14] 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". Another concept introduced in the literature is the cost of risk. Liu and Boggs [15], in their paper on cable life, define the cost of risk as "the cost to a [electric] utility associated with early cable failure" and the cost of failure as "the cost to replace the cable". Liu and Boggs define the cost of risk as the cost of failures that occur before the end of the service life of the product.

Rhee and Ishii [16] introduced a cost-based failure modes and effects (FMEA) approach to measure the cost of risk and apply it to the selection of design alternatives. Kmenta and Ishii [17] use scenario-based FMEA to evaluate risk using probability and cost. Scenario-based FMEA uses predicted failure costs to make decisions about investments in reliability improvement versus maintenance. Taubel [18] implements a similar approach for the calculation of a total "mishap cost" by relating the known costs associated with mishaps to the probability of mishap for different severities of mishap. In Taubel's model, the definition of mishap derives from the Department of Defense's Military Standard 882C [19]: "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.

The models developed in [16-18] form the basis for the model used in this paper, which is described in the remainder of this section. We have extended these models so that technologies can be inserted at various levels of rigor, and there is uncertainty in the life-cycle cost of the system and effectiveness of the technologies in reducing failures. The model in this paper also replaces the FMEA probability of occurrence with discrete event simulation based reliability sampling. The model presented here predicts relative costs (cost differences between cases) rather than absolute costs, and our model is directed toward the activities necessary to implement and qualify a technology insertion (specifically a lead-free control plan).

2.2 Multiple severity model

In order to assess the cost of risk associated with technology insertion (lead-free solder in our case) we will determine the difference in failure consequence costs between the system with and without the technology change. Note that the method described in this section does not calculate the actual life-cycle cost of the system, but rather the cost difference between the resolution and consequences of failure for the two cases while assuming that other life-cycle cost contributions are a "wash". This is referred to as a "relative accuracy" cost model in [20].

Systems can fail in different ways, and all failures do not necessarily have the same financial consequences. A system failure that requires maintenance (repair) might cost less than a failure that requires the system owner to replace the system. Ideally 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 systems, taking into account that those systems can fail multiple times, in multiple ways, and with different financial consequences of failure depending how the systems fail.

Taubel [18] 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., Fig. 1). In the model, each severity level has a distinct cost and an associated probability of occurrence. The area under the curve is the expected total mishap cost.

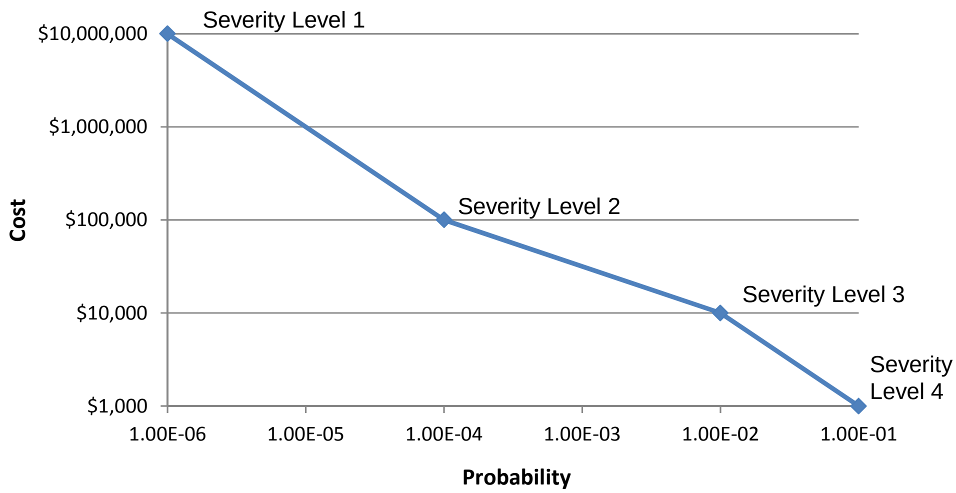

Fig. 1. Multiple severity model (after [18]).

A mitigation activity is a process that may reduce the overall expected number of mishaps at specific 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.

The model described in this section determines the expected number of failures at each severity level rather than calculating the probability of failure at each severity level. This is done because some failures may occur more than once during the life of the product, hence the cost of (multiple) failures is accounted for. We refer to this as the Projected Cost of Failure Consequences (PCFC) for the fleet (population) of products.[1] An overview of the steps in the model is shown in Fig. 2.

The first step in the model is to identify and describe each relevant failure by determining the part affected by the failure, and the failure mode, cause, and mechanism associated with an occurrence of that failure. Additionally, each failure is defined by an application-specific severity level. The severity level determines the cost associated with an occurrence of the failure.

Next, the number of failures expected to occur over the service life of the product at each severity level are determined. This is an application-specific calculation (see the case study in Section 3 for the methodology used). The collective expected number of failures for each severity level is called the severity level profile. The calculation of the expected number of failures per product per unit lifetime for each distinct severity level is given by:

$$f_i = \sum_{j=1}^{n} f_j \tag{1}$$

where f_i is the expected number of failures of severity i per product per unit lifetime; and n is the number of ways a product can experience failure at severity level i.

[1] To clarify, the models used in [18] and in this paper (although not exactly the same – see Section 2.3) are continuous risk models, i.e., they assume that probabilities are continuous, therefore the PCFC is defined as the area under the curve. However, some risk models assume the probabilities are discrete, in which case the cost of failure would be calculated be the sum of the probability of failure at each discrete severity level multiplied by the cost of failure resolution at the corresponding severity level. Both approaches are valid, continuous risk is assumed in this paper.

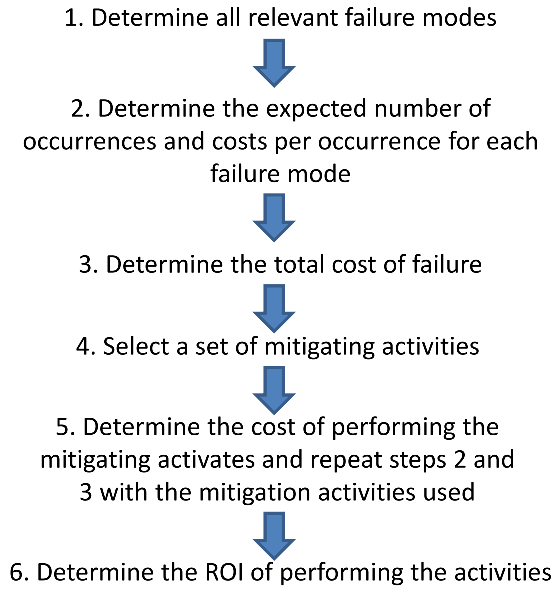

Fig. 2. Modeling steps.

2.3 Using FMMEA data to determine the initial PCFC

Assuming a repairable system, each failure experienced by the system is described by two characteristics: the severity of failure and the frequency of occurrence of that failure. Severity correlates to 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. One possible source of data for determining a PCFC is a Failure Modes, Mechanisms, and Effects Analysis (FMMEA) report (e.g., [21]).[2]

Most FMMEAs in use today qualitatively describe severity and frequency of failure, whereas to be used in this model each failure's severity and frequency must be quantitatively defined. Each failure's severity and frequency will be used to determine: 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.

For example, in the FMMEA used for the case study in this paper, severity of failure is rated on a scale of 1-5, with a severity 5 failure defined as a minor nuisance and a severity 1 failure defined as a catastrophic failure. Each of these severities must be assigned an expected cost associated with the consequences of the occurrence of a failure of that severity.[3]

The transformation of FMMEA ratings to numerical values of cost and expected number of failures is application specific. 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.

Using an expected number of occurrences for each failure severity, and a cost associated with each occurrence at every failure, the PCFC for the system can be determined. 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

[2] A FMMEA categorizes failure events and assigns each event a rating for its severity and likelihood of occurrence. Alternatively, 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. Criticality analysis is a method of prioritizing failures after each failure is assigned a severity and occurrence rating, where the highest priority failures (those to be dealt with first), are those with the highest aggregate severity and occurrence ratings.

[3] It should be noted that FMMEAs also describe the frequency of failure on a qualitative scale (this is usually called the "probability of occurrence"). Kmenta and Ishii [17] use the probability of occurrence; however, in the model presented in this paper, the expected number of failures per product per service life are determined from reliability distributions, not generated from the FMMEA.

occur per product per service life. The service life is the required life the system, expressed in years or temperature cycles. The horizontal axis is the cost per failure event.[4]

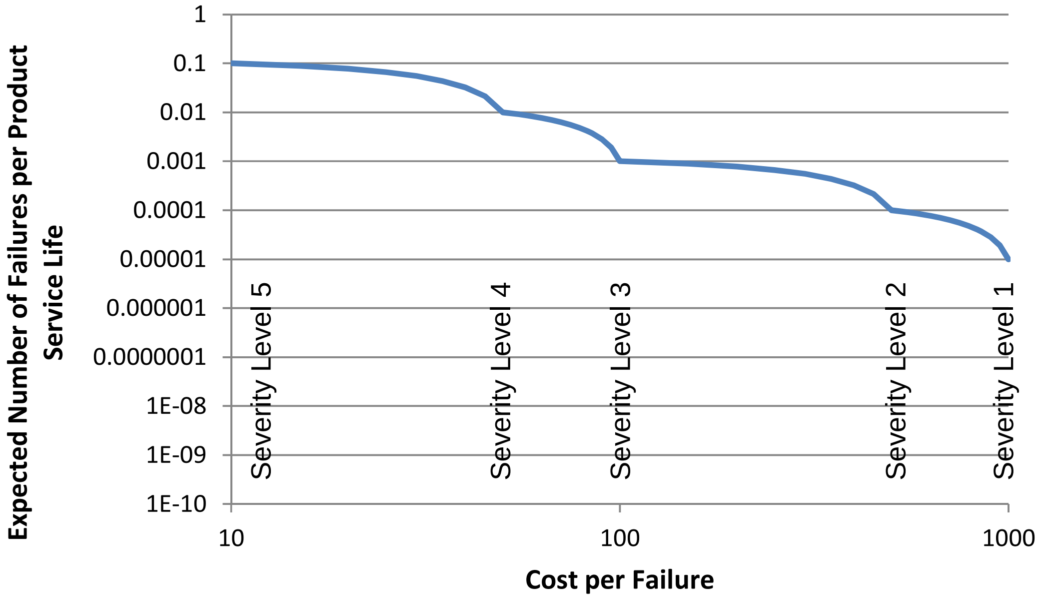

Fig. 3. Expected number of failures vs. cost per failure.

The cost and number of failures for each severity level are connected and form a curve as shown in Fig. 3. The area under this curve is the PCFC for the system.

$$PCFC_{initial} = \int_{E_1}^{E_m} C(x)dx \tag{2}$$

where E_1 is the expected number of severity level 1 failures (E_m is the expected number of severity level m failures); m is the number of severity levels under consideration and $C(x)$ is the cost of a failure event occurring at severity level x.

In practice the area of the discrete trapezoids formed by the points in the curve are determined and summed using,

$$PCFC_{initial} = \sum_{i=1}^{m} \left[E(i+1) + 0.5E(i)\right]\left[C(i+1) - C(i)\right] \tag{3}$$

where $E(x)$ is the expected number of failures per product per unit lifetime of point (severity level) x on the curve.

2.4 Activities that modify the expected number of failures

An activity is sub-process, process, or group of processes that when performed (or applied) changes the expected number of 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 affects the mode, mechanism, cause, or part that corresponded to a failure in the FMMEA used to create the initial severity

[4] The model described in this paper assumes that the cost of failure decreases linearly between severity levels. The assumed linear decrease appears as shown in Figs. 3 and 4 when graphed on a log-log plot. For the plots in the case study, the lines between severity levels are represented by straight lines (on the log-log plots) for graphical convenience.

level profile, then if that activity is performed, the expected number of failures will change. Equation (4) shows the calculation of the new expected number of failures after activities are performed.

$$N_{f-f} = N_{f-i} \prod_{i=1}^{q} P_R(i,R) \tag{4}$$

where N_{f-f} is the number of failures expected to occur over the service life of the product for a particular failure listed in the FMMEA after considering activities; N_{f-i} is the 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)* is the fractional reduction in the expected number of failures to occur over the service life of the product due to performing activity *i*; *q* is the number of activities performed that affect the failure under consideration; and *R* is the level of rigor activity *i* is performed at.

An activity is defined by the change in failures over the service life of the product, the non-recurring (NRE) cost for each level of rigor, and the particular failure modes, failure mechanisms, failure causes, and parts the activity will impact if performed.

The cost of performing all activities, called the Total Implementation Cost, (C_{Total}) is calculated according to,

$$C_{Total} = \sum_{i=1}^{q} C_{NRE}(i,R) \tag{5}$$

where $C_{NRE}(i,R)$ is the cost of performing activity *i* at level of rigor *R*.
Performing an activity at level of rigor *R* may reduce the number of times a failure is expected to occur. The model determines which failures listed in the FMMEA each activity affects by checking if a failure's mode, mechanism, cause, and part are impacted by the activity. The model performs the calculation for each activity on every failure listed in the FMMEA whose mode, cause, mechanism, and part are all impacted by the activity.

Once a set of activities has been chosen, the model calculates the modified PCFC for the system. First the model calculates the number of failures expected to occur at each severity level using Eq. (1) and generates a modified severity level profile. Next, the model uses the new expected number of failures (determined via a discrete event simulation that samples cycles to failure distributions through the support life of the product – see the case study) to calculate expected PCFC of the system using,

$$PCFC_{modified} = \int_{E_{1-f}}^{E_{m-f}} C(x)dx \tag{6}$$

where E_{1-f} is the expected number of severity level 1 failures after activities are considered and E_{m-f} is the expected number of severity level *m* failures after activities are considered.

The difference between the initial PCFC and the modified PCFC, called the *Reduction in Failure Cost* is calculated as,

$$Reduction\ in\ Failure\ Cost = PCFC_{Initial} - PCFC_{Modified} \tag{7}$$

The *Reduction in Failure Cost* can be graphically represented as the difference in the areas under the curves in Fig. 4. 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.

2.5 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 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*,

$$\text{Return on Investment (ROI)} = \frac{\textit{Reduction in Failure Cost} - C_{Total}}{C_{Total}} \tag{8}$$

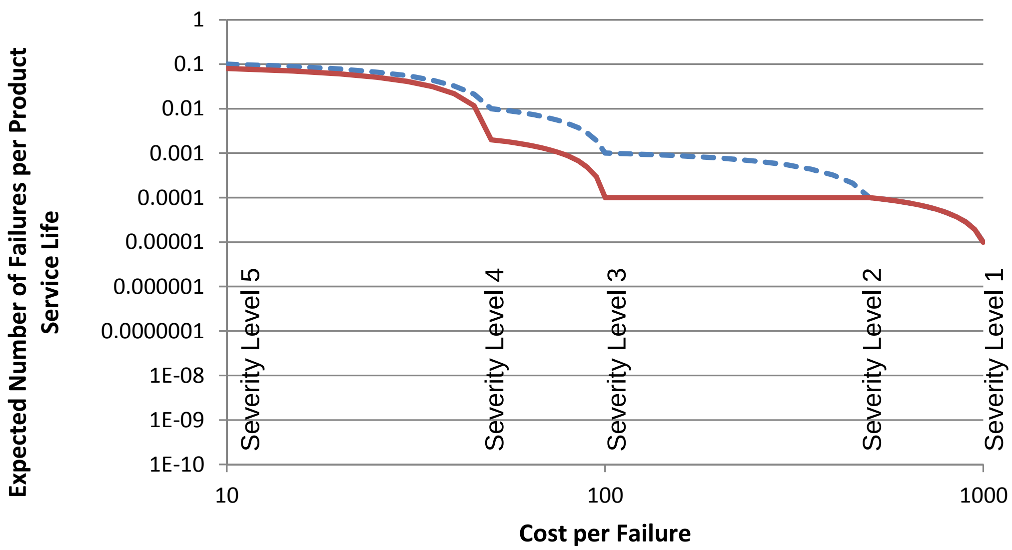

Fig. 4. The blue (dashed, top) curve represents the number of failures per product per unit lifetime at each severity level before activities are considered, and the red (solid, bottom) line represents the expected number of failures with the activities performed.

3. Cost implications of implementing a lead-free solder control plan – a power supply case study

In this section, the model described in Section 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 Power supply description

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 5 shows the power supply's components attached to the printed circuit board (PCB) using both through hole and surface mount. A detailed list of solder connections in the power supply is given in Table 1.

Fig. 5. Components on the PCB.

Table 1
Quantity of 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

Previous analyses of power supplies in the [21] and [22] were used to construct a full FMMEA for the power supply.

We assume that the manufacturer of the power supply has already made the decision to transition to lead-free, or that its transition is required by outside factors (e.g., RoHS legislation). 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. Since lead-free control plan activities only affect solder, we are not considering all failures in the FMMEA, i.e., we will only consider the failures associated with the solder connections of the parts to the PCB - note, tin whisker mitigation activities apply to both the leads and the solder. Table 2 shows the relevant portion of the FMMEA for this case study and categorizes the solder connections on the PCB by type of connection and the parts connected to the PCB.

In the FMMEA, solder connection failures are classified based on the type of part, the size of the connection, and the type of solder connection (through hole or surface mount). For example, in the FMMEA, large through-hole solder joints connecting capacitors are one distinct "part" and there are 4 instances of this in the power supply. Open circuit 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 tin whisker. 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 case study is it assumed that failures associated with intermittent open circuits are less severe than failures associated with permanent open circuits (this is not necessarily always true depending on the application). Note, shock has been omitted from the case study - while shock can be a significant cause of failure in this type of system, it has been omitted to simplify the example.

Table 2
Solder connections portion of the full FMMEA for the power supply.

Number of Parts	Part	Failure Mode	Failure Cause	Failure Mechanism
4	PCB- Capacitor Through Hole Solder Joint- Large	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue*
4	PCB- Capacitor Through Hole Solder Joint- Large	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue

4	PCB- Capacitor Through Hole Solder Joint- Large	Short Circuit	Conductive Bridge	Tin Whisker
16	PCB- Wire Through Hole Solder Joint- Large	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
16	PCB- Wire Through Hole Solder Joint- Large	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
16	PCB- Wire Through Hole Solder Joint- Large	Short Circuit	Conductive Bridge	Tin Whisker
24	PCB- Capacitor Through Hole Solder Joint- Small	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
24	Capacitor Through Hole Solder Joint- Small	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
24	Capacitor Through Hole Solder Joint- Small	Short Circuit	Conductive Bridge	Tin Whisker
22	PCB- Surface Mount Capacitor- 2 Lead Connection	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
22	PCB- Surface Mount Capacitor- 2 Lead Connection	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
22	PCB- Surface Mount Capacitor- 2 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
86	PCB- Surface Mount Resistor- 2 Lead Connection	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
86	PCB- Surface Mount Resistor- 2 Lead Connection	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
86	PCB- Surface Mount Resistor- 2 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
3	PCB- Surface Mount Resistor- 3 Lead Connection	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
3	PCB- Surface Mount Resistor- 3 Lead Connection	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
3	PCB- Surface Mount Resistor- 3 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
1	PCB- Surface Mount Resistor- 8 Lead Connection	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
1	PCB- Surface Mount Resistor- 8 Lead Connection	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
1	PCB- Surface Mount Resistor- 8 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker
2	PCB-IC- 14 Lead Connection	Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
2	PCB-IC- 14 Lead Connection	Intermittent Open Circuit/Cracked Solder Joint	Temperature Cycling	Fatigue
2	PCB-IC- 14 Lead Connection	Short Circuit	Conductive Bridge	Tin Whisker

*Only thermal fatigue is considered in the present model. Fatigue due to mechanical overstress (i.e., drop shock) is not included.

3.2 Environmental and operating conditions, and consequences of failure

This case study analyzes the cost implications of implementing a lead-free control plan for the power supply 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. A desktop computer is in an environment that is assumed to have stable temperatures, pressure, and humidity, while in an aircraft we are assuming that the power supply is operating in the unpressurized, non-climate controlled, tail of the aircraft, colloquially known as the "hell hole." The conditions in the hell hole are assumed to be those defined by [23].

The power supply may also have different service lives and rates of use depending on its application. For this case study, we assume that while a typical commercial aircraft has an expected service life of 20 years.[5] Alternatively, we assume that when the power supply is used in a PC it has an expected service life of 5 years. 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 day, and that it operates 300 days per year. Similarly, we will assume that the PC will

[5] We have assumed that the power supply is not flight-critical hardware. 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. The wait time for corrective action could result in significant financial consequences for the aircraft operator.

encounter 1800 temperature cycles per year (on/off and sleep cycles). Table 3 summarizes the operational expectations of the power supply when used in both applications.

Table 3
Usage conditions for the power supply.

	PC	**Commercial Aircraft**
Temperature Cycles (per lifetime) (*c*)	9000	36000
Service Life (Years)	5	20
Temperature Cycles Per Year	1800	1800
Number of Units in Service	100,000	500

The consequences of failure for a power supply in an aircraft can be far greater than for a power supply in a desktop computer. In the context of this paper, we consider the consequences of failure in terms of the financial loss to the entity or entities responsible for the performance of the system. 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 4 shows the assumed consequences and likelihoods of varying severity and occurrence ratings of failure when the power supply used in a desktop PC and a commercial airplane.

Table 4
Consequences and likelihoods of varying severity and occurrence ratings of failure for the power supply used in a desktop PC and a commercial aircraft.

	Desktop PC		**Commercial Aircraft**	
Severity of Failure	**Failure Event Associated With:**	**Failure Cost**	**Failure Event Associated With:**	**Failure Cost**
5	Minor Nuisance	\$10	Minor Nuisance	\$100
4	Repair of Power Supply	\$75	Repair of Power Supply	\$2,500
3	Replacement of Power Supply	\$150	Replacement of Power Supply	\$5,000
2	Replacement of Power Supply, collateral damage to PC	\$750	Repair or Replace, Interrupting Flight Schedule	\$25,000
1	Loss of Entire PC	\$1,500	Repair or Replace, Causes Collateral Damage	\$250,000

In this case study we assume that all repair and replace maintenance actions associated with a part result in a good-as-new part in the product. 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 1) do not change if multiple no fault found events occur on the same board.[6]

In the case study in this paper the lead-free solder was assumed to be SAC305 solder and its cycles to failure is modeled with a Weibull distribution,

$$F(c) = 1 - e^{-\left(\frac{c-\gamma}{\eta}\right)^{\beta}} \tag{9}$$

where $F(c)$ is the cumulative distribution of failure; c is the number of temperature cycles (Table 4); β is the Weibull shape parameter; η is the Weibull scale parameter; and γ is the Weibull location parameter.[7] A value of 2.9 was assumed for β based on testing done by [24] and [25], however, characteristic life (η) of SAC305 solder for the conditions in the case study are not well known so a range of values from 25,000 to 75,000 cycles was assumed in the results that follow, the location parameter (γ) was assume to be zero in all cases.[8]

[6] Some organizations have policies limiting the number of no fault found events. These policies may require that if a board has encountered a specific number of no fault found events (for example three), and the underlying cause is not discovered, the board is thrown away. Adapting these policies within the model would require that a third severity level 5 event on a particular board would actually be a severity level 3 event; however this case has not been considered in this case study.
[7] We have assumed for this study only that all the relevant failure mechanisms are driven by temperature cycling.
[8] In reality, the Weibull parameters would be expected to differ for the SMT vs. through-hole solder joints, and for the same solder joints in the two different environments considered in the case study, however, insufficient data exists to represent this differentiation.

A discrete event simulator that sampled the respective cycles to failure distributions for each of the product's parts was used to determine the sequence of failure events (a Monte Carlo approach was used). The discrete event simulator was run through the entire service life of the product to determine the total failure counts for each part in the product. 100 independent time histories of the products analyzed in the case study were run to build the results provided.

3.3 Lead–free control plan activities

The lead-free control plan is a set of activities that a manufacturer can choose or be required to perform to ensure product performance.

The activities considered in this paper, summarized in Table 5, are from the PERM working group [4]. For this study, the activities are applied to both applications of the power supply (in a desktop computer or commercial aircraft). Note: the standard was written for the aerospace high-reliability electronics industry. It is not in general use in the commercial computer industry.

Table 5
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 lead-free solder or finishes. Include limitations on incompatible materials, environmental conditions, maintenance, rework, and repair and other risks.	solder joint intermittent and open circuits	fatigue stresses, over loads, poor quality	Material fatigue due to 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 maintenance and support	Are the requirements of this standard applied equally to original equipment manufacturing and repair, rework, maintenance and support activities?	solder joints intermittent and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	Material fatigue due to temperature cycling and tin whisker
System reliability	Are the effects of lead-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 intermittent and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	Material fatigue due to temperature cycling and tin whisker
Product and system level reliability	Qualification of the lead-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 intermittent and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	Material fatigue due to temperature cycling and tin whisker
Environmental and operating conditions	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 intermittent and open circuits; short circuits	fatigue stresses, over loads, poor quality and conductive bridge between conductors	Material fatigue due to temperature cycling and tin whisker

The system implementer may have the choice to perform or not perform each activity in the control plan, and 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" assumed in this case study are given in Table 6.

Table 6
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 Change in Failures over the Product Service Life	Mode	Low	High
1	1.00	-	-	-
2	1.00	-	-	-
3	Triangular Distribution	0.85	0.70	1.00
4	Triangular Distribution	0.50	0.40	0.60
5	Triangular Distribution	0.25	0.15	0.35

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

3.4 Case study results

Each application of the power supply was run for 100 trials (life histories). Each trial calculates the initial PCFC by sampling the cycles to failure distributions for each part in the product (see analysis description after Eq. (9)). In this paper, each solder joint on the power supply represents a socket (a place where a part goes). Each socket must complete the number of cycles 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 cycles to failure distribution 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. 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.

Desktop Computer Results. In this section, the lead-free control plan is applied to the power supply used in a desktop computer. The results of the case study are shown in Figs. 6 through 9, where the blue (dashed) lines represent the system before the lead-free control plan activities are performed, and the red (solid) lines represent the system after the lead-free control plan activities are performed. Note that while 100 trials were performed, Figs. 6 and 8 only show the results of 15 of the trials. Figs. 7 and 9 show histograms of all 100 ROIs that were calculated.

In Fig. 6 and the similar figures that follow, 15 trials (randomly selected from the 100 generated) are shown. Each trial represents one possible future for the system. In Fig. 6 the system without the lead-free control plan activities (the blue dashed line) generally have a higher expected number of failures than the system after control plan activities are performed, however this is not universally true, in a few trials performing control plan activities leads to a worse result. Note, performing control plan activities does not make the cost of failure lower (we assume that the same failure always costs the same to resolve). Any positive return on investment is the result of changes in the number of expected failure events or changes in the severity of the failure events.

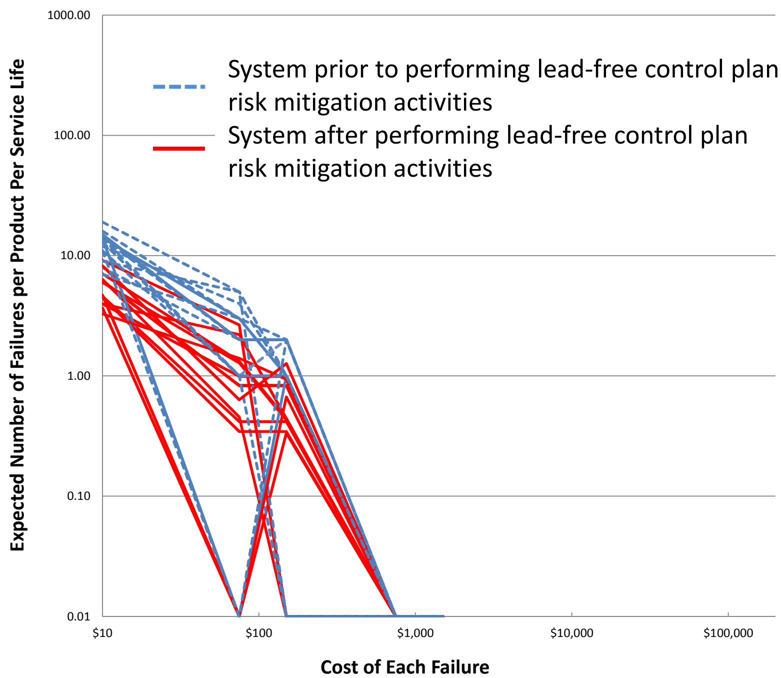

Fig. 6. Results for the PC, η = 25,000 cycles.

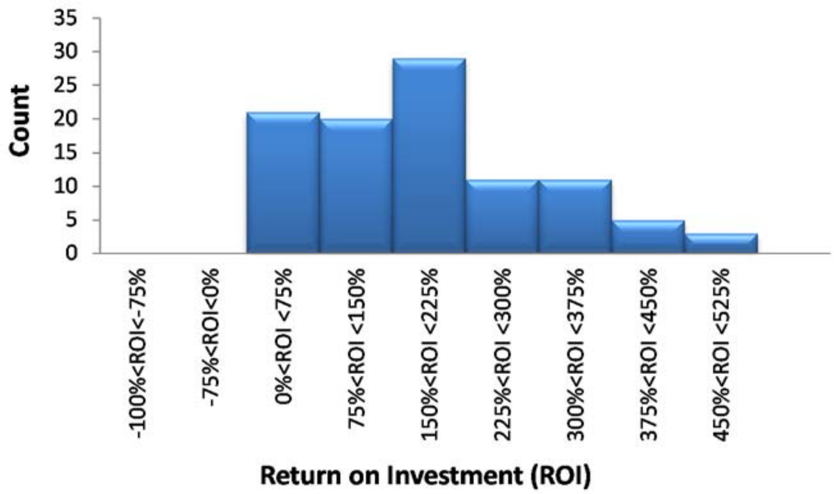

Fig. 7. Histogram of ROIs for the PC, η = 25,000 cycles.

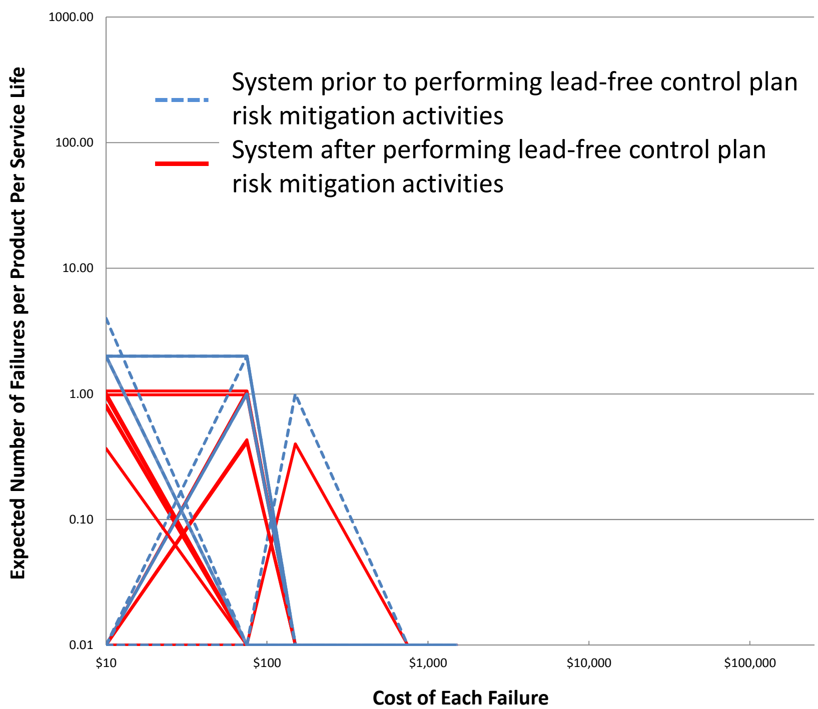

Fig. 8. Results for the PC, η = 50,000 cycles.

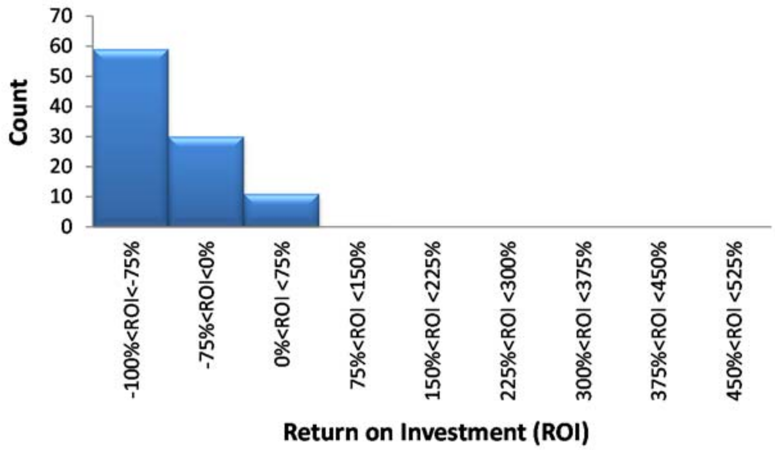

Fig. 9. Histogram of ROIs for the PC, η = 50,000 cycles.

When η = 50,000 cycles 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 90% of the trials. But, when η = 25,000 cycles, the initial PCFC is large enough that paying for activities to reduce it is cost effective. Results for η = 75,000 cycles also appear in the summary (Table 7).

Commercial Aircraft Results. Next we perform the case study again for the power supply in a 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, and the service life of the aircraft is 20 years. As in the PC case study, the study is run for varying values of the characteristic life of the solder. Figs. 10 to 13 show the results.

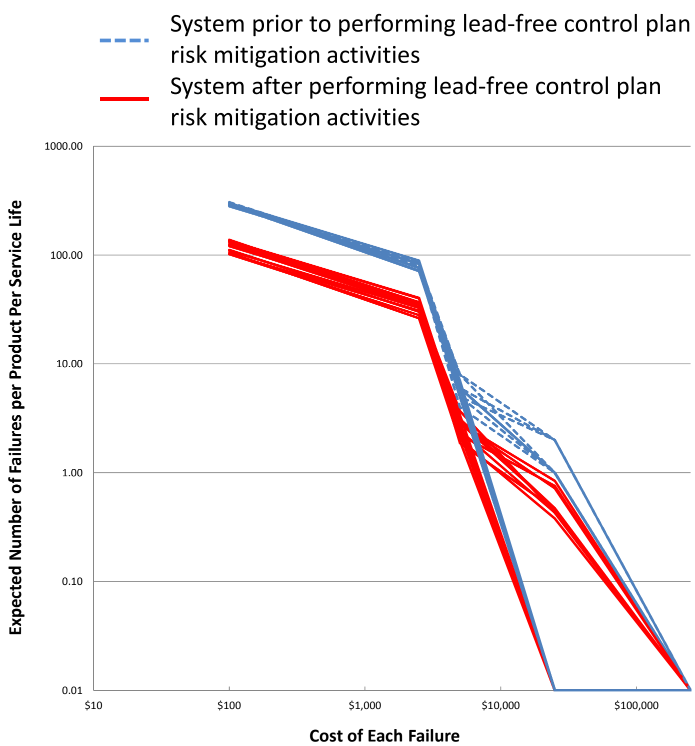

Fig. 10. Results for the commercial aircraft, η = 25,000 cycles.

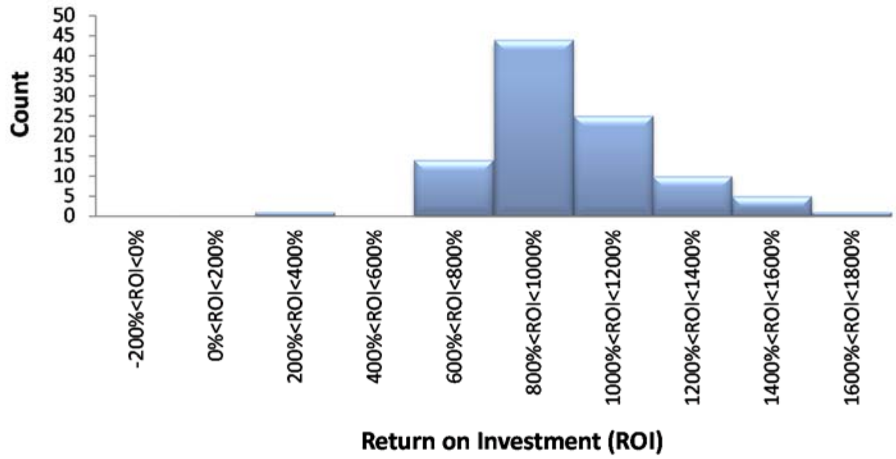

Fig. 11. Histogram of ROIs for the commercial aircraft, η = 25,000 cycles.

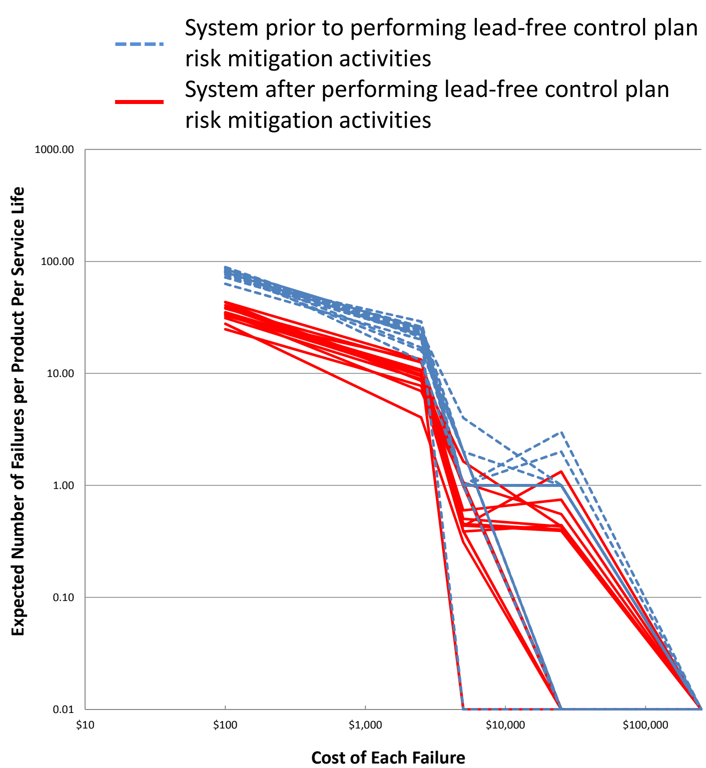

Fig. 12. Results for the commercial aircraft, η =50,000 cycles.

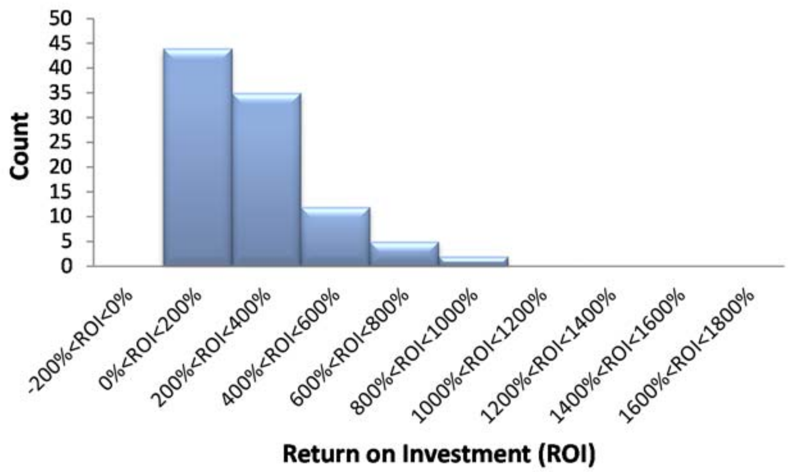

Fig. 13. Histogram of ROIs for the commercial aircraft, η = 50,000 cycles.

Case Study Summary. Table 7 shows the minimum, median, and maximum values of ROI for each of the cases considered.

Table 7
ROI Values for all cases considered.

		η = 25,000 cycles	**η = 50,000 cycles**	**η = 75,000 cycles**
PC	Median ROI	189%	-78%	-100%
	Minimum ROI	4%	-100%	-100%
	Maximum ROI	523%	48%	28%
Commercial Aircraft	Median ROI	956%	240%	130%
	Minimum ROI	344%	70%	-73%
	Maximum ROI	1633%	928%	897%

The model indicates that performing activities provides more value in the commercial aircraft scenario than the PC scenario. Performing activities is only viable 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.

Performing Activities at the Highest Level or Rigor. If the lead-free control plan activities are performed at level 5 rigor for the commercial aircraft case (instead of level 3 assumed in the results shown in Figs. 12 and 13), the result in Figs. 14 and 15 are obtained.

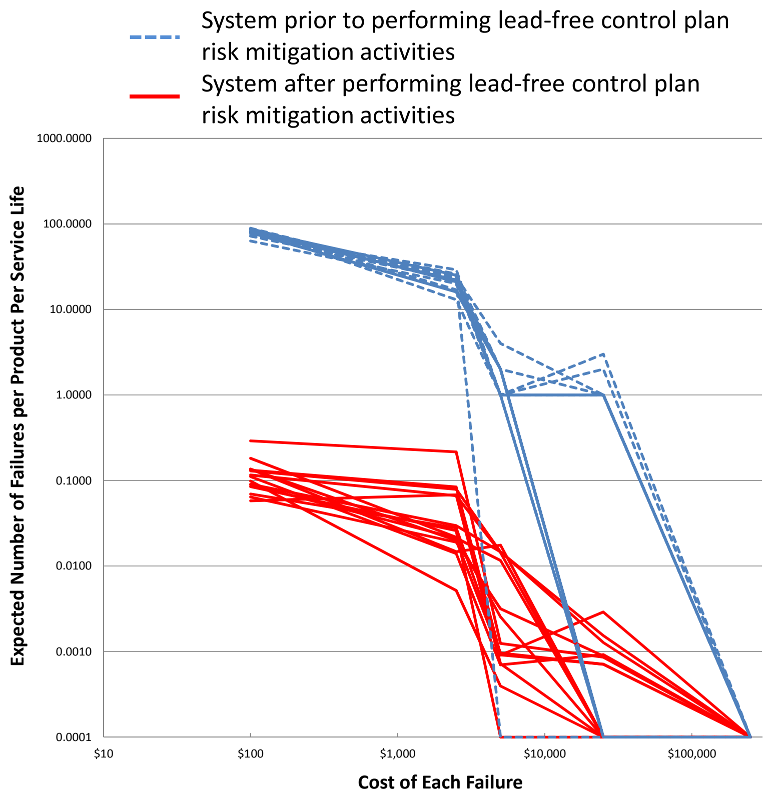

Fig. 14. Results for commercial aircraft, η =50,000 cycles, activities performed at the highest level of rigor (level 5).

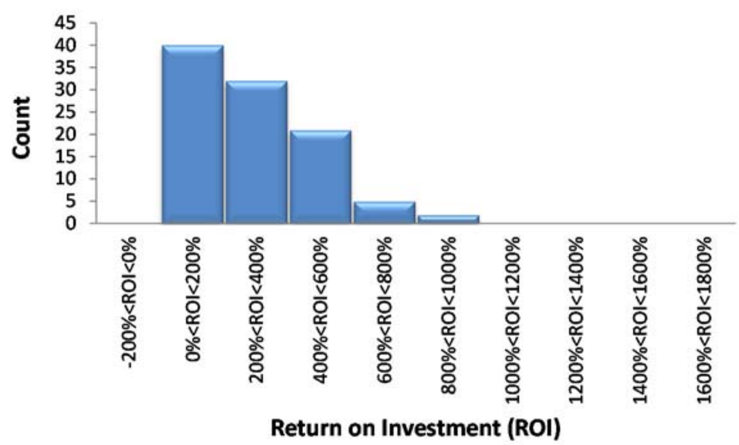

Fig. 15. Histogram of ROIs for the commercial aircraft, η = 50,000 cycles, activities performed at the highest level of rigor (level 5).

The median ROI when all activities are performed at level of rigor 3 is 240% 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.

Activities that are not Independent. In all the cases considered so far, 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 realized. 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 they are required to do so by regulation or the customer), 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 level 3 of rigor and the other with activities performed at the level 5 of rigor. The results are shown in Figs. 16 through 19.

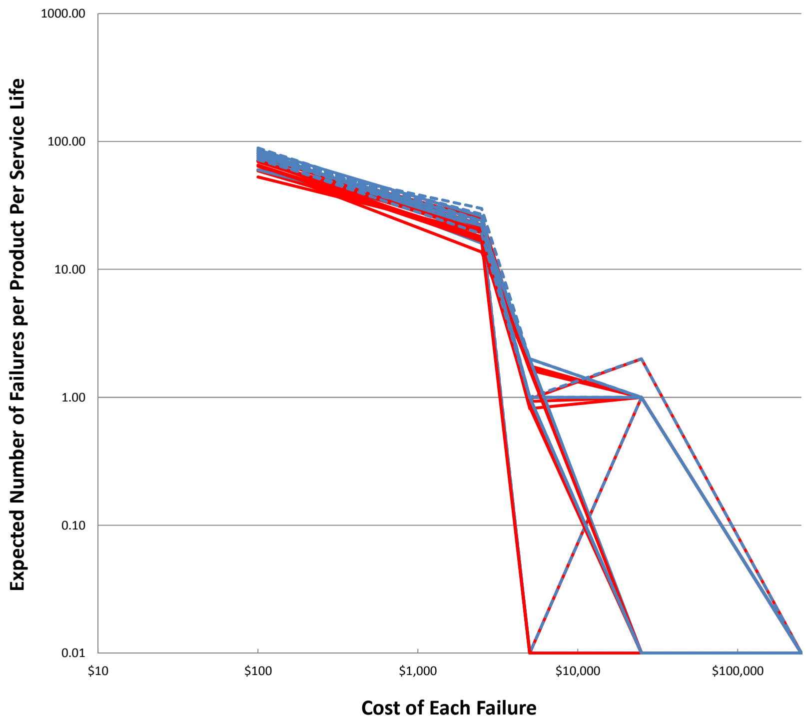

Fig. 16. Results for the commercial aircraft, η = 50,000 cycles, activities performed at level of rigor 3, activities are not independent.

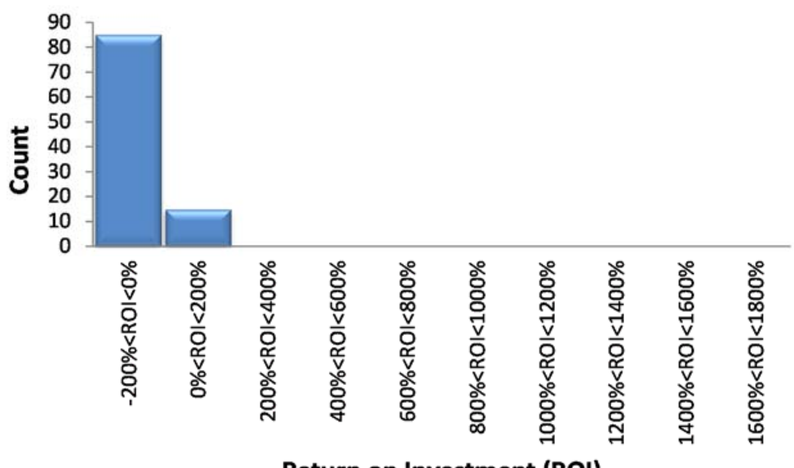

Fig. 17. Histogram of ROIs for the commercial aircraft, η = 50,000 cycles, activities performed at level of rigor 3, activities are not independent.

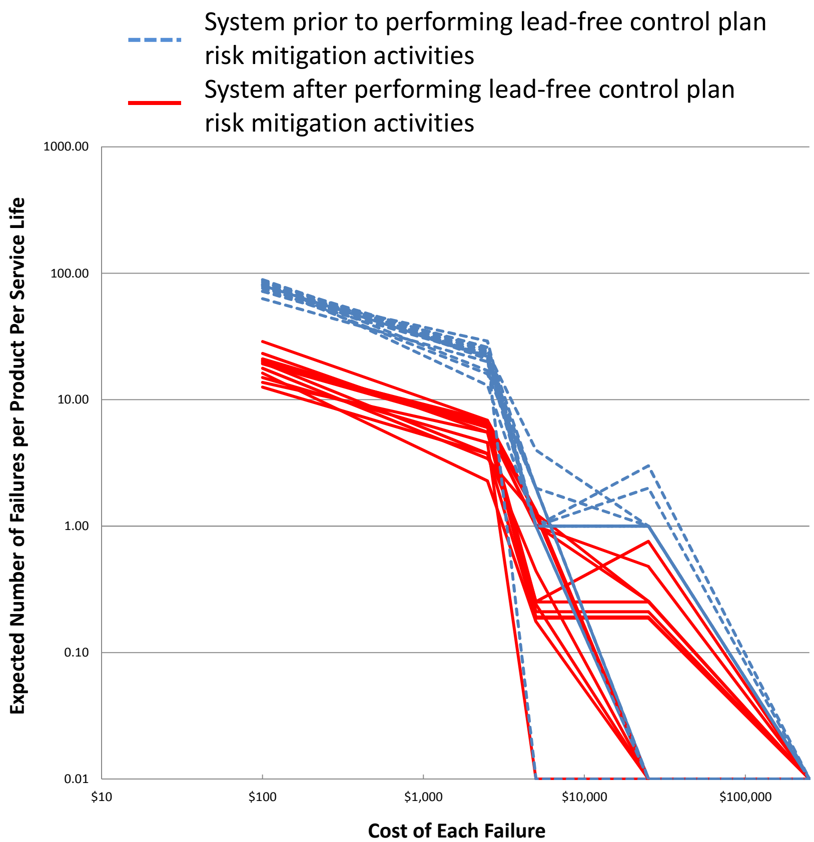

Fig. 18. Results for the commercial aircraft, η = 50,000 cycles, activities performed at level 5 of rigor, activities are not independent.

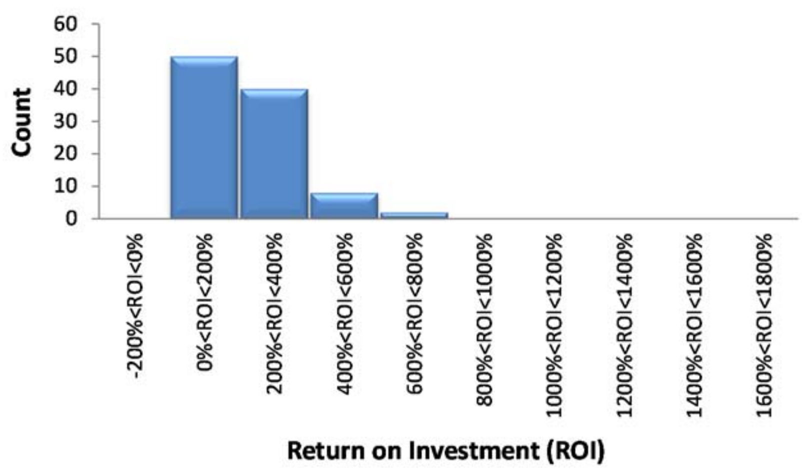

Fig. 19. Histogram of ROIs for the commercial aircraft, η = 50,000 cycles, activities performed at level 5 of rigor, activities are not independent.

The median ROI when activities are not independent and performed at level of rigor 3 is -26%, and when activities are performed at level of rigor 5 is 175%. Clearly, when activities are not independent, their effectiveness is reduced.

4. **Summary and Discussion**

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-based FMEA model that forecasts the cost of risk associated with inserting a new technology into a system has been used to assess a lead-free control plan for the same product in various risk scenarios. In the model 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.

The case study presented assesses the adoption of a lead-free solder control plan (required by customers) into a system that previously used tin-lead solder. The case study applied of the model to two applications: a power supply in a personal computer (PC) and in a 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 the cost-effectiveness of performing some or all of the activities in the control plan. In the case study performed for this paper, 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 supporting 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.

The basic model presented in this paper assumes that the risk mitigation activities are independent of each other, that is performing one activity does not affect the benefit associated with performing another.[9] This will not always be the case, since multiple activities may impact the same failure mechanism. The current 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 current 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). Additionally, some activities may be effectively "grouped", i.e., one activity may be a pre-requisite for another. While correlating inputs in the model may accommodate some of the possible dependencies, fundamental changes to the architecture of the model could be needed.

Redundancy in systems potentially needs to be accommodated in the model. In the aircraft case study in this paper, the power supply is assumed to be non-flight critical and therefore redundancy has been ignored. If the power supply was a flight-critical item, it could be redundant with another identical power supply, and if the power supply being modeled fails the redundant 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 severe enough that the aircraft cannot take-off because the power supply needs to be replaced before scheduled maintenance. However, the present model does not consider the situation where one power supply fails, the redundant power supply takes over, and then the redundant power supply also fails in the same flight (and the power supply is flight critical). 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. Treatment of flight-critical systems would potentially also require modeling common-mode failures and single point of failure analysis. For flight critical systems, the redundancy could triple or quadruple the interconnect count, but potentially reduces the likelihood of the most severe failures.

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[9] An example of the non-independence of activities is considered at the end of Section 3.4 (Figs. 16-19), however the non-independence of activities is potentially much more complex than the example provided.

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