# ABSTRACT

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| Title of Document: | A COST MODEL FOR ASSESSING THE TRANSITION TO LEAD-FREE ELECTRONICS |
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Actions such as the WEEE Directive and RoHS Directive are forcing electronics suppliers to transition their products from tin-lead to lead-free solder in order to support consumer goods. The defense and avionics industries obtain their parts from the same suppliers and must adapt to these new lead-free products. In this thesis, a cost model was created to evaluate the transition from lead-free to tin-lead electronics. The model provides the industry with multiple transition options and determines the costs associated with each of these options. The options modeled are an all tin-lead assembly, a lead-free assembly and a mixed assembly. The cost model assimilates all the costs involved in the transition to lead-free and includes changes in reliability, and plan development and maintenance costs. The model requires users to input information specific to their organization. The model also predicts costs incurred when more than one plan, i.e., a specific set of materials and qualifications, must be supported.

# A COST MODEL FOR ASSESSING THE TRANSITION TO LEAD-FREE ELECTRONICS

By

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# Dedication

This thesis is dedicated to my mother and late father. I am grateful to my father for pushing me towards the science and tech field and basically for being one of *those* dads. I am grateful to my mother for continuing to keep my father's expectations alive these past 4 years of my education.

I would also like to dedicate this thesis to my friends, roommates and officemates in graduate school. Without them and their distractions, I am pretty sure this would have been completed 6 months ago.

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# Chapter 1: Introduction and Background Research

## Electronic Waste Concerns

In the recent past a lot of emphasis has been placed on recycling electronic components and developing products that have minimal impact on the environment. The long term goals of many developed countries include reduction of hazardous materials, reduction of generated waste, improved recovery and recycling of products and reduced energy use [1]. The motive behind this trend is the reduction of exposure to substances that pose a risk on the environment and human health. Government agencies are beginning to focus on the impact of these substances and are passing legislation for their regulation. Industries in turn are faced with pressure from the government and consumers to reduce the usage and disposal of harmful substances.

A primary concern regarding generated waste, specifically electronic waste, is the disposal of lead into the environment. Lead is a major component of electronic products and since electronic waste is growing at three times the rate of other wastes, there is a significant amount of lead being released into the municipal waste stream [1]. Since lead is a highly toxic substance, it is considered calamitous to human health. When exposed, lead has the tendency to enter the human body and remain there. This causes short term and long term effects depending on the intensity of the exposure. Short term exposure to high amounts of lead can lead to diarrhea, vomiting, convulsions, coma and death. On the other hand, long term exposure to lower levels of lead may be asymptomatic but still severe. Long term effects of lead poisoning on children include lower IQ, slower body growth, behavior problems, sleep issues, etc. The younger population is more vulnerable to lead since they absorb lead more easily. Lead is also known to cause miscarriages and stillbirths for expectant women [2].

Due to the numerous and severe health complications discussed above, lead is rated by the United States Environmental Protection Agency as one of the top seventeen chemicals that pose the direst threat to human health. Consequently, substantive steps have been taken in the United States to minimize lead exposure to the environment. Lead based paints have been banned since 1978 and legislation was passed to remove lead from existing houses. A significant fund of $10 billion over 10 years was allocated for this purpose, thereby reiterating the toxicity of lead exposure and the need for urgent action. More regulations including the Lead Tax Act (June 1993), Lead Exposure Reduction Act (May 1994) and California Waste Recycling Act (September 2003) were passed to minimize lead use and lead waste for the same reasons [1].

The European Union has also taken definitive steps towards minimizing the use of hazardous substances in the environment through banning and recycling. Two actions that were enforced recently that are specifically directed at the electronic industry are the Waste from Electrical and Electronic Equipment (WEEE) Directive (2002/95/EC) that took effect on August 13, 2005 and Regulation of Hazardous Substances (RoHS) Directive (2002/96/EC) that took effect on July 1, 2006 [3].

### *WEEE Directive*

The objective of Waste from Electrical and Electronic Equipment Directive (WEEE) is to reduce waste from electrical and electronic products and components;

promote reuse, recycling and other forms of recovery of such wastes; and to improve the environmental performance of all producers involved in the life cycle of electrical and electronic products [4]. The WEEE directive states that '*The purpose of this directive is, as a first priority, the prevention of waste electrical and electronic equipment and in addition the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste. It also seeks to improve the environmental performance of all economic operations involved in the life cycle of electrical and electronic equipment and in particular operators directly involved in the treatment of waste electrical and electronic equipment*' [4, 5]. The ten categories of electrical and electronic equipment recognized and regulated by WEEE are large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment, electrical and electronic tools, toys, leisure and sports equipment, medical devices, monitoring and control instruments, automatic dispensers. WEEE stipulates that these electronics be recycled using the guidelines provided. Within these categories, WEEE specifically states that '*components containing lead will have to be removed from any end-of-life electrical and electronic equipment (EEE) that is destined for landfill, incineration or recovery*' [4]. For this recycling initiative, WEEE dictates the producers as being financially responsible for the collection and treatment of waste electronics. Consequently, WEEE makes the manufacturer proactive in enhancing recycling as well as designing parts with minimum harmful elements in use which in turn minimizes the amount of hazardous substances such as lead in the environment.

### *RoHS Directive*

The Restriction of Hazardous Substances Directive (RoHS) was designed to supplement the WEEE Directive to enhance recycling and decrease the use of hazardous substances. The Directive states that '*The purpose of this Directive is to approximate the laws of the member states on the restrictions of the use of hazardous substances in electrical and electronic equipment and to contribute to the environmentally sound recovery and disposal of waste electrical and electronic equipment*' [5, 6]. Like WEEE, the Directive covers equipment that are dependent on electrical currents or electromagnetic fields in the following categories: IT/telecommunications, electrical and electronic tools, consumer equipment, large household appliances, small household appliances, lighting equipment, toys, leisure and sports equipment, and automatic dispensers. RoHS is very specific and requires that member states will not have products in these categories in market that contain the following materials: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) [6]. The term Maximum Allowable Concentration (MAC) was created by RoHS to define the permissible limits of the banned substances. It was decided that lead, mercury, hexavalent chromium, PBB and PBD may represent 0.1% by weight in homogeneous materials and cadmium may compose 0.01% by weight in homogeneous materials [5]. Such specific stipulations force manufacturers to reevaluate product design without the mentioned substances and adapt manufacturing processes to accommodate the new ban and display RoHS compliance.

### *Exemptions to the Directives*

Both RoHS and WEEE allows for exemptions in cases where compliance is not immediately practical. RoHS exemptions include lead in glass cathode ray tubes, lead in high melting temperature type solders, lead in solders for network infrastructure systems and lead in electronic ceramic parts. The rationale behind these exemptions is that the lead present in these products cannot be easily substituted due to unavailability of safer elements that will perform the same function or due to the fact that the negative effect on the health and environment upon substitution will outweigh the positive effects [5, 6]. For its part, WEEE exempts defense equipment, that typically requires high functional reliability and therefore cannot accommodate material and process changes swiftly, but clearly states that this does not apply to products that are not intended for military purposes. It is understood that all possible lead substitutions will have to undergo extensive testing to ensure that they maintain the high reliability and performance intended. This makes immediate substitution infeasible and the implementation of RoHS becomes a slower process for the defense industry. Unlike WEEE, RoHS does not cover electronic medical instruments and monitoring and control instruments and these devices are not subject to the ban due to the fragile nature of their applications.

## Compliance

### *Detection Technologies*

The establishment of the RoHS Directive requires manufacturers to show compliance with the ban of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE). As of yet there are no standardized tests that can be used to display compliance, thereby leaving manufacturers to decide for themselves their method to display compliance. There are two ways compliance can be displayed. One, manufacturers can obtain verification of compliance for procured materials, parts and subassemblies from all their suppliers and archive the information. Two, different methods of chemical analyses can be conducted to determine the presence of the banned substances in their products [7]. Clearly, it is better to invest in an analysis technology that analyzes the substance content than to rely upon second hand information provided by suppliers. As a result, numerous techniques are being investigated and developed by scientists and engineers for the sole purpose of determining compliance.

Non-destructive x-ray fluorescence mapping analysis is an example of an evaluation technique to determine lead content. X-ray mapping images of different elements such as lead, tin and silicon are closely examined and then compared to the x-ray mapping image of the solder. This allows the manufacturer to quantitatively determine whether the lead presence exceeds the allowable limit. Moreover, this method helps distinguish between restricted materials such as lead solder and exempted materials such as leaded glass and electronic ceramics. This is a novel method to detect the presence of not only lead but also cadmium and determine their permissibility in the product [8].

Another detection method for lead determination is through microwave assisted inductively coupled plasma optical emission spectrometry (ICPOES) [9]. In this method, lead concentration is determined in a sample cell and calibration points are obtained for lead at various wavelengths versus various concentrations. The spectrophotometer and the calibration points are then used to determine lead concentration in the sample in question. ICP-OES as a tool for lead detection has a high precision of R.S.D. less than 3% and repeatability less than 15%. Moreover, it delivers results in a short amount of time making it a good detection technique for RoHS compliance [9]. With such high precision technologies available and even better approaches being developed, the manufacturer has no choice but to comply with the regulations.

### *The Eco-Efficient Perspective*

The literal reason behind the RoHS Directive and WEEE Directive is to reduce the amount of harmful substances in the environment, subsequently reducing human exposure to these substances. Implementation of RoHS and WEEE, however, should be considered from an eco-efficient point of view. This means that methods where maximum environmental gains can be achieved at minimal cost must be highlighted. This truly serves the spirit of RoHS and WEEE since sometimes the strict judicial and literal enforcement may lead to less than optimal effects on the environment while at the same time driving costs higher. One way to achieve eco-efficiency is to replace end-of-life physical weight of the product with its environmental weight in the recycling streams. This environmental weight is determined by assimilating the environmental weight of the materials which are replaced by the recycled materials in their second life and all environmental loads incurred due to the replacement and recycling process. This replacement allows the manufacturer to determine whether each of processes is having a negative or a positive impact on the environment [10].

### *LEAP Working Group*

As already mentioned, most aerospace and defense applications are exempt from RoHS compliance. Commercial electronics manufacturers however are required to deliver lead-free products. This discrepancy in products becomes an issue since the aerospace and defense industries rely on the same suppliers as commercial manufacturers for their electronic parts. The electronics suppliers tend to focus on the needs of the commercial manufacturers since more of their revenue lies in that sector and not the defense sector. Because of this greater demand and revenue from the commercial sector, eventually all new products will be introduced only in the RoHS compliant, i.e., lead-free form. It is imperative therefore that the aerospace and defense industry adapt to lead-free parts. This of course is no easy issue since their applications are extremely high risk and require high reliability. Moreover, parts are subjected to extreme use conditions and product life cycles are measured in decades and not months or years. Most repair and maintenance work does not happen until years after manufacture. These issues make it difficult for the aerospace and defense industries to cleanly switch to lead-free parts. Extensive reliability testing must be done before a tin-lead part can be replaced with a lead-free part in order to maintain the high degree of reliability required while maintaining the desired performance [11]. The aerospace and defense industry is therefore faced with a conundrum.

The shared concerns regarding the impact of lead-free on the aerospace industry due to the eventual unavailability and necessary reliability of parts has prompted the formation of the Lead-free Electronics in Aerospace Project (LEAP) Working Group. This group is sponsored by Aerospace Industries Association (AIA), Avionics Maintenance Conference (AMC) and the Government Electronics and Information Technology (GEIA). The group represents most of the world's major aircraft manufacturers and defense contractors as well as mid-tier suppliers and government organizations (AIA) and came into existence in 2004 purely for the purpose of addressing issues raised by the 2006 RoHS Directive and its effects on the different stakeholders. The LEAP Working Group immediately recognized that since the aerospace industry is driven by the same market forces that drive the consumer products, the non-compliant lead based parts will quickly become unavailable. For the purposes of reliability and sustainability the group is pushing for more research to be done on all potential new alloys and parts. One of the major actions of the LEAP Working Group is that it continues to develop guidance documents so the current standards can soon become international norms for all concerned in the industry. There is a general attempt to bring the entire defense industry on the same page regarding actions taken to transition to lead-free parts. The LEAP Working Group along with the GEIA has already published the following guidance documents and most of them have been accepted by International Electrotechnical Commission (IEC) and some are pending acceptance [12]:

- **GEIA-HB-0005-1:** *Program Management/Systems Engineering Management Guidelines for Managing the Transition to Lead-free Electronics (GEIA: 30 June 2006, IEC: 21 December 2006)*

This document acknowledges that lead-free may impact reliability and performance and illustrates what concerns should be voiced in the development of the product. This document was developed for the program manager and lead systems engineer to assure proper program execution and customer satisfaction.

- **GEIA-HB-0005-2:** *Technical Guidelines for Aerospace Electronic Systems Containing Lead-free Solder (GEIA: 31 December 2006, IEC: 30 June 2007)*

  This document provides technical guidance for the use of lead-free and mixed systems. It discusses topics such as high performance electronics testing, analysis of tests and data, lead-free solder behavior, solder joint reliability, printed wiring boards and assemblies, assembly and wiring conditions, repair and rework etc.

- **GEIA-STD-0005-1:** *Performance Standard for Aerospace and Military Electronic Systems Containing Lead-free Solder (GEIA: 30 June 2006, IEC: 31 December 2006)*

  This plan requires the user documentation of all Lead Free Control Plans (LFCP) so that plan owners, customers and stakeholders are assured of the integrity of the aerospace and high reliability electronic systems.

- **GEIA-STD-0005-2:** *Standard for Mitigating the Deleterious Effects of Tin in High-Reliability Electronic Systems (GEIA: 30 June 2006, IEC: 31 December 2006)*

  Tin will become a common material used in place of lead in the new electronic products. Tin brings with it the anomaly of tin whisker growth which is a reliability concern and yet to be well understood and controlled. The purpose of this document is to provide a framework for the control of tin whisker growth as well as specify that users develop and implement as well as document Tin Whisker Mitigation Plans.

- **GEIA-STD-0005-3:** *Reliability Testing for Aerospace and High-Performance Electronics Containing Lead-free Solder (GEIA: 30 September 2007, IEC: 31 December 2007)*

  Several major reliability testing is nearing completion but it will be some time before the data can be characterized and understood. Meanwhile, many manufacturers need initial understanding of their products and must conduct testing on their own. This document provides a default method for reliability testing in the near future when little or no other information is present regarding reliability testing and analysis of lead free electronic equipment.

- **GEIA-STD-0005-4:** *Impact of Lead-free Solder on Aerospace Electronic System Reliability and Safety Analysis (31 January 2008):*

  This document quantifies the effect of lead-free solder on system reliability and certification analysis.

- **GEIA-HB-0005-3:** *Repair and Rework of Electronic Assemblies Containing Lead-free Solder (31 December 2007):*

  This document provides guidelines for the maintenance and repair of the lead-free electronics in a manner that maintains their integrity [11, 13, 14].

## Cost Modeling for the Transition to Lead-Free

As mentioned before, there is a general trend towards products that minimize harmful effects on the environment and human health. This trend is further reinforced by the RoHS ban on harmful substances and WEEE regulations on recycling and minimizing of electronic wastes. In addition to legislation enforcement there are emerging detection technologies to enforce compliance. With all of these, and the general push towards eco-efficiency and green electronics, manufacturers have very few options and excuses to avoid the oncoming adoption of lead-free electronics. Of course such an action as switching materials, manufacturing processes and assembly processes from tin-lead options to lead-free has substantial cost and reliability implications. Moreover, the burden of the ban of materials and recycling will almost entirely be shouldered by the manufacturer and supplier. Therefore, there is a dire need for the development of a cost model that will display to manufacturers the cost burden of switching from tin-lead to lead-free. Such a cost model should be adaptable to manufacturers of all sizes and all products, and must consider different options for adapting to the lead-free trend by performing cost comparisons between the different options available.

## Making the Transition to Lead-Free

The previous section explored the inevitability of lead-free products becoming standard. However, moving from a tin-lead based operation to an entirely lead-free system is no easy task and requires an appreciable amount of research and testing effort. First, potential lead-free alloys must be identified. These alloys then need to undergo a qualification process where their performance in different assembly processes is evaluated. The different assembly and manufacturing processes then need to be modified to adapt to this new substance. All of these steps translate into costs incurred by the manufacturer and potential effects on reliability of the part and the system. The technical problems associated with obtaining the new alloys, the difficulties posed by using them in assembly and manufacturing processes and the associated reliability concerns, all of which ultimately increase costs, will be discussed in this section.

### *Lead-free Alloys*

Choosing lead-free alternatives to substitute tin-lead in electronic parts is not easy since there are a lot of requirements a lead-free alloy must satisfy to match the functionality and reliability of tin-lead solders. It is imperative that the lead-free alloy not compromise the reliability of the system it is incorporated into. Some of the requirements the alloys must satisfy when compared to their tin-lead counterpart include low melting point, low or comparable cost, low toxicity, comparable phase transition temperatures and wetting features, acceptable physical and mechanical properties, comparable or enhanced reliability, compatibility with lead containing parts and manufacturing processes, and environmental stability [5]. Desired physical and metallurgical properties include low melting temperature and good metal-wetting ability and the element that most fulfills these requirements is tin. It is therefore practical for the lead-free alloy to be tin based. However, there are only a limited number of elements than can be alloyed with tin and still maintain the desired characteristics. These elements are silver, bismuth, copper, indium, nickel and antimony [1]. Tin is alloyed at different concentrations with one or more of the elements listed to achieve an acceptable alloy. In general it is preferred that the alloys be near eutectic [5].

Once the alloys have been chosen for substitution, the question of the availability of these elements and the costs involved in procuring them presents itself. Metals such as silver are expensive to mine and require significant amounts energy and thereby produce significant waste. Moreover, silver is an expensive metal, making it expensive to use in electronic parts. Such an expensive metal may increase the cost of the solder. Another issue is that the higher concentration of tin in the new lead-free ores requires more tin to get extracted and the extraction process of tin leaves behind radioactive wastes as a bi-product which must be disposed of properly, thereby driving costs higher. These sort of issues put recycling back into the equation to prevent the need to obtain materials as well as a method to save money for both manufacturers and consumers [1, 5].

### *Manufacturing and Reliability Issues*

Manufacturers are forced to use alternative lead-free solders in heterogeneous assemblies with large and small components. The primary differences between the lead-free alloys and tin-lead alloys arise in melting temperature, wetting ability of soldered materials, thermal resistance, mechanical fatigue resistance and thermal fatigue resistance. These differences present reliability issues when substituting the lead-free alloys for tin-lead alloys. Therefore, the prediction of lifetime and reliability data of the new products becomes imperative, especially for mid to small sized manufacturers who may not have the resources to conduct research to obtain such information. It is agreed that the reliability of the new lead-free solder should not be lower than the standard tin-lead solder since it would severely compromise the integrity of the product. For this reason and due to the short amount of time available to achieve compliance or adapt to the available supply, the lead-free solders must undergo accelerated tests such as dry heat, temperature cycling, thermal shocks, mechanical charges, electrical charges and thermo mechanical charges to determine reliability data [15].

In addition to subjecting the solders to accelerated tests, the manufacturing and assembly methods must also be customized to the new solders since the new alloys have different properties. It has been determined that the biggest discrepancies in manufacturing requirements, when using lead-free alloys instead of tin-lead alloys, arise due the lead-free alloys' higher melting temperature and worse wettability when compared to conventional solders [1]. The higher melting temperature can be attributed to the higher tin concentration in lead-free alloys. Since tin has a higher melting point, the alloys too have a higher melting point. The increased tin content also increases susceptibility to corrosion. This same high tin content may also lead to brittle intermetallic formation between the pad and the solder making the joint weak and susceptible to cracking. Moreover, it is crucial that the manufacturing process enable the correct amount of wettability to be achieved to protect components from breaking. Issues such as these are especially obvious when considering the assembly processes of wave soldering and reflow soldering.

Reflow soldering is a common method for attaching surface mount components. The solder paste is applied to the Printed Circuit Board (PCB) and the devices are positioned appropriately. The solder paste is then melted in an oven and this leads to the soldering of the components to the board. Since lead-free alloys have a higher melting temperature, they require a higher peak reflow temperature. This higher temperature also exposes the PCB and other components to higher thermal stress than they are normally used to. Since it is difficult to control the temperature of the entire board, it is entirely possible that the temperature at some parts of the board may exceed what the board or components are designed for. To avoid such thermal stress issues, it is necessary that the PCBs be adapted to higher temperatures and better mechanical resistance to distortion [16]. The ovens must also be efficient enough to heat PCB assemblies to these higher melting points in a short amount of time. In general, convection ovens are preferred to the traditional infra-red ovens used in lead-free soldering since these ovens minimize temperature variations on the board and also provide mechanical support to prevent distortion due to high temperature. Lead-free soldering is also difficult to achieve due to the smaller difference between the melting point and soldering temperature [16].

Wave soldering is a process where the components are placed on to the PCB and the loaded PCB is then passed across a wave or cascade of solder. It is important that the set of temperature and fluxing system is determined to be appropriate for the individual product. Same as in reflow soldering, high temperatures may cause distortion and therefore rigid support is required. Another problem faced during lead-free wave soldering is the phenomena of creating excess dross on the solder surface. Nitrogen needs to get incorporated into the soldering process to minimize this. In addition to this, soldering in nitrogen environments also shortens wetting time, allowing shorter soldering time which in turn may lead to lesser mechanical stress on the PCB. In addition to corrosion due to high tin content, another problem faced by soldering equipment at high temperatures is the dissolving of the iron from the equipment which leads to solder contamination [16].

It is important to note that there are solutions for the problems faced by reflow soldering and wave soldering such as ternary alloys that have better wettability and are more resistant to creep and temperature changes. Also, the addition of metals such as bismuth and indium lead to a reduction in melting temperature. However, creating multiple alloys increases costs directly because of the need for more materials and multiple alloys are difficult to control and less stable due to numerous intermetallic phases [16]. This in turn affects reliability and further adds to the cost burden. The higher temperature requirements also translate to higher energy demands and costs and with the conventional sources of energy available, the environment ultimately suffers, thereby defeating the purpose of RoHS and WEEE. Clearly, the incorporation of lead-free substances has manufacturing and material demands that greatly affect the cost.

### *Tin Whiskers*

The transition to lead-free electronics has driven the selection of pure tin and high tin alloy finishes due to their excellent solderability, corrosion resistance, low contact resistance, low cost and compatibility with both lead-based and lead-free solders [17]. Both pure tin and tin alloys bring with them the risk of tin whisker formation. Tin whisker risk is a major reliability concern when lead-free deposits are implemented [18]. Normally for a tin-lead alloy, it is the presence of lead that mitigates the formation of tin whiskers [19]. A tin whisker can be defined as a tin crystal that grows out of tin-finished surfaces. A whisker is normally a long, needle-like growth. There are other forms of growth such as hillocks which are less than 10µm and do not pose threats [20]. It is necessary for any tin whisker growth to happen that the energy of the system is lowered and that there is a place for tin atoms to move to at the whisker grain boundary [17].

Tin whisker formation can cause electrical shorting between adjacent leads of a component, leads of adjacent components and between the leads of a component and traces on the printed circuit board. Bridging risk can also increase when the tin whisker separates from the original component and falls onto two adjacent conductors [19]. It is assumed that tin whisker formation is due to energy release driven by compressive stresses associated with tin plating. These stresses may arise due to intermetallic compound formation between the tin and substrate material, residual stresses in the tin plate from the electroplating process, mechanical loading, surface damage and mismatches in the coefficient of thermal expansion between the plating and substrate or underlayer in the presence of a temperature excursion [20, 21].

Intermetallic formation is a diffusion based phenomenon that promotes tin whisker growth. Intermetallic formation leads to compressive stresses in the tin deposit if the intermetallic is not formed uniformly. For some alloys intermetallics can be formed at room temperature and exposure to annealing temperatures like 150˚C may reduce irregular growth and compressive stresses. Alloy densities play a big role in influencing compressive stresses. Intermetallics will also alter the lattice structure which may compress the remaining tin layer and apply tension to the substrate. Electrodeposited finishes are also more susceptible to tin whiskering since they form columnar grains and can induce lattice defects and stacking faults that yield compressive stresses. The electroplating chemistry and processes such as impurities, organic additives and current density of the plating bath will affect the number of defects and residual stresses in the deposit. In addition to intermetallic formation, mechanical loading can also create localized stresses that produce whiskers in tin deposits. Surface damage and imperfections may also create stress that promotes whisker formation [20].

Several tin whisker mitigation strategies are currently being investigated. Some of these include conformal coating, different electroplating techniques, surface treatment, different tin alloys, under-layer material and annealing. Conformal coating is applied to suppress the growth of tin whiskers. However, it is entirely possible, depending on the type and thickness of coating that after some period of time the tin whisker will penetrate through the coating and become a risk. As for electroplating techniques, the formation of tin-oxide layer on the tin plating surface increases the stress in the tin plating and at the locations where the oxide film breaks, increasing the chances of tin whiskers forming. However, a uniform intermetallic layer between the tin plating and the substrate will create less stress [19].

Two of the tin whisker mitigation strategies being investigated are surface treatment on lead-frame substrate before tin plating and surface treatment of the tin layer. Surface treatment on the tin plating of the lead-frame prevents whisker formation. For example, tin whiskers on fine pitch connectors can be prevented by surface roughening. As for surface treatment of the tin layer, since the formation of $Cu_6Sn_5$ intermetallic compound between the tin layer and copper substrate contributes to the increase in compressive stress in the tin plating, a material layer can be deposited onto the copper substrate before plating the tin layer. Ideally, the underlayer material will form intermetallic compound at the layer interface but induce inductively lower stress in the tin plating. Nickel and silver underlayers mitigate tin whisker growth. In addition to surface treatments, high temperature annealing, which involves heating and cooling a structure to relieve residual stresses, may reduce tin whisker growth [19].

## Costs Involved in Lead-free Transition

The costs incurred by the manufacturer doing lead-free assembly can be broadly classified into two categories: fixed costs that do not change with production volume and variable costs that typically include labor and materials and have a direct relationship to production volume. Therefore, the manufacturer has to take several costs into consideration when implementing lead-free assembly processes. There is the bare element cost of the solder constituents and the cost of the alloy. The solder product cost can then be determined by assimilating all the costs factors involved in the manufacturing hierarchy for the solder itself. As explained before, since there is a discrepancy in reflow and wave soldering for lead-free alloys when compared to traditional tin-lead alloys, there is some amount of increased operational costs involved to implement lead-free. An overall cost of the system should include solder product cost, operational costs as well as the board and component costs [1].

Implementing RoHS would result in an initial increase in costs for the manufacturer when considered from a traditional cost accounting point of view. Control costs such as capital, labor and materials would initially increase since the old system would have to be overhauled for the new system and new machinery would have to be acquired and labor trained. Moreover, environmental costs would be a new class of control costs and there maybe hidden environmental costs such as penalties, fines as well as the cost of pollution. Material costs also get more expensive with lead-free since the alternative materials are more expensive. Also the technical manufacturing and reliability issues discussed above would create a significant cost burden from the reliability perspective. All of these effects, incorporated in a traditional cost model show an increase in expenses.

The cost of RoHS implementation should also be treated as a life cycle costing problem. Life cycle costs include not only the costs involved in manufacturing the component until it is shipped out but the entire life cycle of the product, which includes the raw material extraction at the beginning through the material disposition. Activity based costing works on the general principle of activity based management and highlights the resources (materials) being consumed by activities (manufacturing). It can be used to identify the true costs of the process and can be used to segregate overhead costs and apply them to all processes proportionately. This will help the manufacturer identify what lead-free process is affecting the cost the most. While conducting a precursory cost estimate of the implementation may not show immediate profit, assimilating the life cycle costs is necessary [5].

### Cost Models for Lead-free Transition

Cost is a primary driver for all manufacturers when making changes in their assembly processes and product line as would be required for the lead-free implementation. However calculating a general percentage increase in manufacturing costs is not particularly useful to determine the cost impact of this lead-free implementation. As explained before, a detailed cost breakdown of all processes is necessary to determine the cost impact. Very little has been published on quantifying the costs, manufacturing or life cycle, associated with the use of lead-free electronic parts. With the exception of one paper that is discussed below, all references to cost in the literature are qualitative in nature.

Palesko researched the cost impact of lead-free manufacturing as a Fulbright Fellow at the Osaka University [22]. She analyzed the key cost differences in all aspect of lead-free manufacturing flow to compare the differences between lead-free and tin-lead manufacturing. The software used is called SavanSys and the four major areas targeted were materials, components, processing and yield since these seemed to be most affected. The lead-free cost model was applied to a variety of sample designs to demonstrate cost differences related to design style and size. The cost model was applied to a generic cell phone board with 65 actives and 535 passives, a signal analyzer board with 80 actives and 121 passives and a small, portable consumer device with 21 actives and 231 passives.

SavanSys creates cost models by dividing the process into activities and then determining costs and yields. The model capabilities include determining cost and yield of the substrate running a substrate process flow, adding cost and yield of components, defining cost and yield of board activities and board fabrication activities and defining test and rework activities. The basic information required, but not limited to, for all of the capabilities discussed are time, operator and equipment utilization and cost, defects, tooling costs and materials and amounts used. Different models may require additional information.

The SavanSys cost model was fed the required information for each of the four areas discussed above and the reasoning behind the cost assumptions were explained. For example inspection steps in the area of processing may take longer due to inexperience and the fact that lead-free solders are not as ‘shiny’ as the typical leaded solder. This expectation is accommodated as a higher cost for that process step. The costs accumulated from the four different cost models were then applied to designs for a generic cell phone board, a signal analyzer board and a small portable consumer device. The four costs were accumulated and the model predicted an increase in the manufacturing cost of these items as lead-free with the cell phone having the highest percentage cost increase. The main objective behind the activity was to display the approach to cost modeling based on activities or processes and the idea of cost estimation due to changes in the nature of the product.

Over the course of the analysis Palesko discovered that lead-free costs when dealing with a large board is different for a smaller board. A small board size with limited number of components will have assembly and fabrication costs as the major cost components when transitioning to lead-free. Larger boards on the other hand, depending on cost and volume of components, have either substrate fabrication or components cost as the major economic bulk. Boards with very high component counts will have a very expensive assembly process regardless of board size. Palesko focuses only on manufacturing costs and does not address the life cycle cost impact of the transition to lead-free solder.

## Thesis Objectives and Tasks

The purpose behind this thesis is to provide the defense and avionics industry with the costs associated with transitioning from traditional tin lead products to lead free products. As discussed before, there are a lot of reliability issues when implementing parts made of new materials. This is especially dangerous when considering the high risk and long term nature of defense operations. In order to determine the costs involved with this transitioning, a life cycle cost model was created that assimilates costs such as program development costs, reprocessing costs and reliability maintenance costs. The user is also provided with different options on how to tackle the inevitable unavailability of tin lead parts and the costs associated with each option.

The thesis will do the following:

- Introduce the cost model
- Describe the algorithms associated with the different costs
- Introduce options and assumptions
- Display sample set of results
- Draw conclusions

# Chapter 2: Modeling Approach

The last chapter explained how the defense and avionics industry needs to adapt to the RoHS ban on lead, despite being exempt, since they draw their parts from the same suppliers that manufacture consumer products that are required to comply with the ban. An adaptation to new solders is a huge undertaking due to the high risk nature of flight and other defense operations and the fact that the new lead-free materials have to be tested and qualified for use in the specific applications. This will manifest a financial burden on the industries that supply the defense and aircraft manufacturing communities. This chapter focuses on the cost model that was created to assess these financial ramifications of switching to lead-free products. The model itself is a general assimilation of all costs involved in the transition and the calculations and theory involved in each of the assimilated costs will be explained in detail in this chapter.

The general approach of the model for the transition to lead-free parts is to assimilate the costs involved cumulatively for a specified number of years. This same approach will be applied to a number of different options created to manage the transition to lead-free solder. In the end, the model will provide the user the cumulative cost of each of the different options allowing them to choose the option that works the best for them. In order to determine these different costs, several effects must be modeled. One of these effects includes the variation of the number of parts available as tin-lead or lead-free as a function of time. The cost of adapting to this availability will reveal itself as reprocessing costs which is the cost involved in reprocessing lead-free parts to tin-lead parts or vice versa. The reprocessing costs may accrue per board, per part and/or per I/O. The reprocessing costs will bring with it fixed costs such as the tooling and training required for reprocessing. There will also be other fixed costs such as process and part qualification to determine what parts to use and how to assemble them on to the boards in a manner that ensures that the new boards with lead-free parts will meet the same performance and reliability standards as the boards composed of tin-lead parts. Non-recurring engineering costs such as plan development incorporating the lead-free parts must also be accounted for. Moreover, if parts are reprocessed or mixtures of lead-free and tin-lead parts are used, the reliability of the parts and the board is expected to be affected. In these cases there will be costs involved in qualifying the solder as well as testing the reliability of the parts reprocessed using the new solder. Once changes in the reliability are forecasted, sparing costs, which are dependent on the number of boards required, must be calculated and accommodated in the financial report.

One major feature to be kept in mind about the model described in this chapter is that it is a ‘relative’ cost model. This means it provides cost estimates that are relative to or measured from the cost associated with the system if there was no transition to lead-free. The model therefore considers a lead-free transition scenario and provides the user with how much more or less it will cost to manufacture and sustain a system in that specific scenario as compared to the same system costs when there is no RoHS regulation. Therefore, any cost that is not directly related to the change in availability, reliability, or ease of assembly of tin-lead/lead-free parts is not included in the model. In other words, a cost that will be incurred by the manufacturing organization regardless of whether the part being use is tin-lead or lead-free, such as packaging costs or shipping costs is of no significance to the model. Essentially, the model is based on changes in key quantities rather than all the quantities themselves. For example, the number of spares an application requires is not as important as the additional spares that are required because of the use of new lead-free parts. The reason for using a relative approach is that cost differences are easier to model as well as more accurate than absolute costs. Moreover, cost differences also provide an easier method of comparison for the user and better financial understanding of the effect of the transition to lead-free parts.

### Model Formulation

As explained before, this relative cost model estimates the cost of transitioning to lead-free parts by assimilating all costs involved that are directly affected by the unavailability of conventional tin-lead parts, which are then accumulated over time. The components affected by the transition to lead-free electronics include boards, parts, solder etc., and there are several factors that affect the costs incurred due to this transition. For example, the model incorporates the fact that the availability of lead-free and tin-lead components will change over time. Early in the transition there should be a fair amount of conventional parts available, but later the number of parts available in the tin-lead form will decrease as suppliers begin to exclusively cater to the lead-free demands, which is their primary market. The industry may choose to adapt to this unavailability of tin-lead parts by adopting reprocessing techniques for the boards and reprocessing costs may be incurred per board, pert part, per I/O, etc. In addition to the reprocessing cost, there will be other fixed costs that must be considered, such as the non-recurring engineering costs of program development, and process and material qualification. The reprocessing techniques must also be qualified. The new tin-lead solder (and components that use it) must also undergo qualification tests before being implemented for large scale use. The designated plans including the new materials and their associated processes will also require maintenance costs every year. It is however possible that once the program has been installed, and processes qualified, the recurring costs of reprocessing and program maintenance may eventually decrease. The other issue that arises due to changes in manufacturing techniques and new materials is a change in reliability. Reprocessing parts may affect reliability of the part and the lead-free parts may have a reliability that is different from the conventional tin-lead products. Higher temperature assembly processes may contribute to reliability changes in the part and board as well. In addition, the new lead-free alloys are more susceptible to tin whisker precipitated failure. These reliability changes are accounted for in the cost model in the form of sparing costs. The annual recurring costs therefore will mainly comprise of sparing costs, reprocessing costs and program maintenance costs.

All the effects the cost model accounts for are detailed in (1).

$$C_{T_i} = \frac{\sum_{j=1}^{N_{rp1}} C_{rp1_j} + \sum_{j=1}^{N_{rp2}} C_{rp2_j} + C_{spares} + C_{plan} + C_{plan\ maint}}{(1+d)^{i-1}} \tag{1}$$

where

$N_{rp1}$ = number of parts that need to be reprocessed from tin-lead to lead-free in year i
$C_{rp1}$ = cost of reprocessing one part from tin-lead to lead-free
$N_{rp2}$ = number of parts that need to be reprocessed from lead-free to tin-lead in year i
$C_{rp2}$ = cost of reprocessing one part from lead-free to tin-lead
$C_{spares}$ = cost of additional spares needed because of reliability decrease in year i (could be negative if a reliability increase is realized)

$C_{plan}$ = NRE cost of plan development and implementation in year i
$C_{plan\ maint}$ = cost of plan maintenance in year i
d = discount rate on money
i = year (starting with year 1).

The first term in (1) is the cost of reprocessing tin-lead parts to lead-free and the second term represents the cost of reprocessing lead-free parts to tin-lead. The number of parts that need reprocessing in either case is obtained directly from the fraction of parts that are only manufactured as tin-lead or lead-free for a given year. The third term is the cost of the spares or more accurately the change in the cost of spares due to the reliability changes. The next term is the cost of plan development to adapt to the lead-free transition and the last term is the plan maintenance cost which is a fraction of the plan development cost. In (1), only the cost of plan development is a non-recurring engineering cost. All other costs are incurred every year. The denominator in (1) accounts for the cost of money over time. $C_{Ti}$ is the total cost in the $i^{th}$ year in equivalent year 1 dollars.

## Reprocessing Costs

Reprocessing costs comprised the first two terms in (1) and describes the cost involved in changing a tin-lead part to lead-free and vice versa. Reprocessing costs are included in the model since an organization may choose to deal with all its parts either in the lead-free or tin-lead form. In that case, the parts that are not available in the desired form must be reprocessed. Equation (2) describes how these reprocessing costs are calculated by the model. The first term is the recurring cost for each part that has been reprocessed and the second term is the cost of reprocessing each of the parts.

$$C_{rp} = C_r + N_{io}C_{io} \tag{2}$$

where,

$C_r$ = recurring cost per part reprocessed
$N_{io}$ = number of parts I/O per part
$C_{io}$ = reprocessing cost per part I/O.

It should be noted that the non-recurring cost of qualifying a reprocessing process is included in the non recurring engineering cost of plan development and implementation. Looking at (1) and (2), it can be seen that the number of total I/Os must be determined. To do this the number of applicable parts must be determined. The number of applicable parts can be determined by directly multiplying the total number of parts to the fraction of parts that are only made in the form that is not desired. This will yield the number of parts that need to undergo reprocessing. Equation (3) describes the method for obtaining the number of parts that need to be reprocessed.

$$\begin{aligned} N_{rp1} &= f_{TL}N \\ N_{rp2} &= f_{LF}N \end{aligned} \tag{3}$$

where,

$f_{TL}$ = fraction of parts only available as tin-lead parts
$f_{LF}$ = fraction of parts only available as lead-free parts
N = total number of parts.

$N_{rp1}$ gives the number of parts that must be reprocessed from tin-lead to lead-free when supporting an all lead-free process and $N_{rp2}$ gives the number of parts that need to be reprocessed from lead-free to tin-lead to support a conventional tin-lead assembly process.

The two fractions in (3) above, $f_{TL}$ and $f_{LF}$, can be obtained from a profile that describes the availability of tin-lead and lead-free parts over the number of years being considered in the model. This profile is based on supplier decisions to manufacture parts exclusively as tin-lead or lead-free form and the changes in these decisions over the years in an attempt to adapt to lead-free parts and changing customer demands. Figure 1 shows the assumed availability of parts as only lead-free or only tin-lead over a period of 10 years. The vertical axis of the profile is the fraction of parts whereas the horizontal axis is the year. Note that for most of the years, the fraction of parts available as tin-lead and the fraction of parts available as lead-free do not add up to 1. This is because an overlap in parts is assumed, i.e., a fraction of the parts that are available in both forms. The plot at the top with closed triangles is the fraction of parts that is only available as lead-free and the lower plot

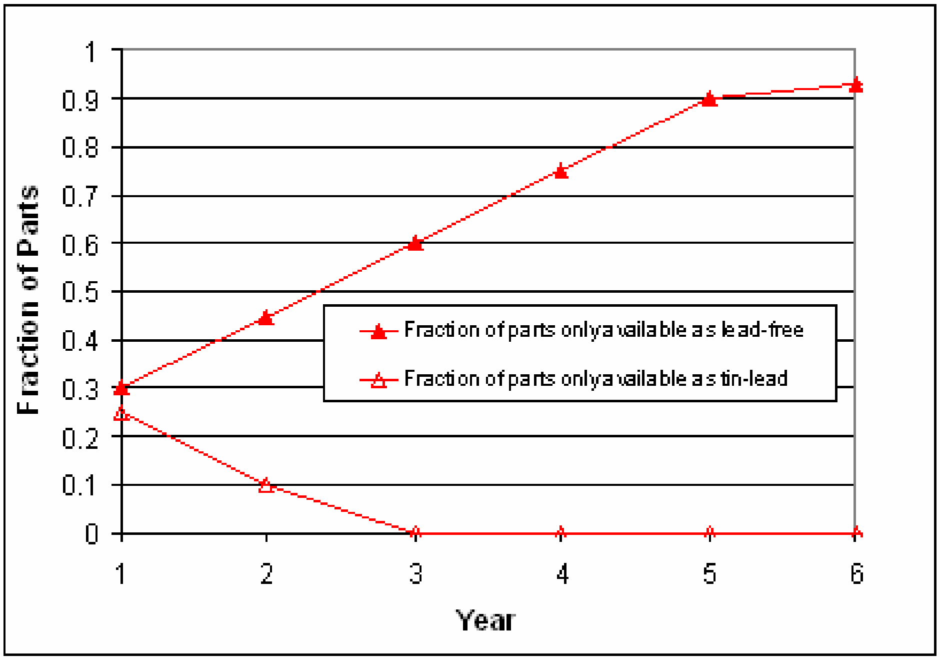


**Figure 1: Availability of Lead-Free and Tin-Lead Parts**

with open triangles is the fraction of parts only available as tin-lead. With the RoHS and WEEE and other pending directives enforced, eventually the fraction of parts only available as tin-lead will approach zero and nearly all parts will be available as lead-free.

Two practices that will affect the reprocessing costs incurred by the manufacturing organization are lifetime buys and bridge buys. A lifetime buy occurs when the company purchases enough parts to last the lifetime of the intended application [23]. A bridge buy happens when enough parts are purchased to last until the next design refresh. The parts purchased in lifetime or bridge buys are called legacy parts and it is general practice for legacy parts to be purchased for a certain percentage of the total parts for a specific number of years. For the purposes of this model, this would mean that the organization has an existing inventory of parts in the conventional tin-lead form that it can choose to use or not use.

Figure 2 shows this modification to the availability profile if the legacy tin-lead parts are available from a lifetime buy for 30 percent of the total stock for a period of 5 years. The lines with no triangles display the adapted profile with the impact of legacy tin-lead lifetime buy parts accounted for. The fraction of parts only available as lead-free is lower the first 5 years since there are legacy parts available in the tin-lead form. Therefore, the fractions of parts only available as tin-lead is also a little bit higher due to the existence of this legacy buy. These legacy parts will have effects on the recurring costs. For example, in order to sustain an all tin-lead assembly, a certain percentage of parts that are only available as lead-free will have to get reprocessed. But now with the lifetime buy these parts are already bought and do

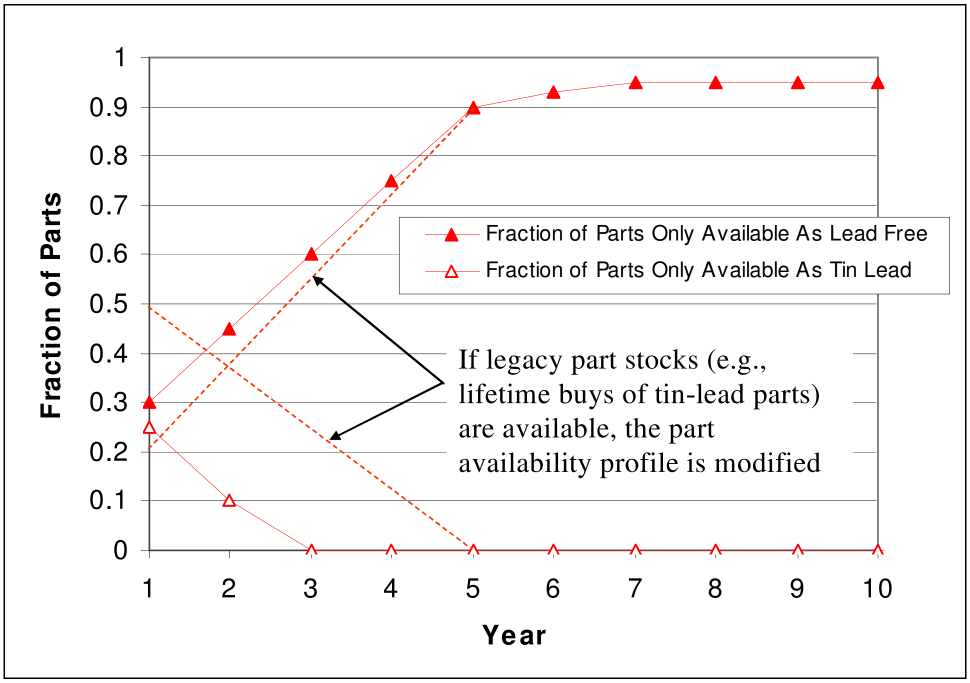


**Figure 2: Modified Profile due to Legacy Parts (legacy parts shown for 30% of parts for 5 years)**

not need reprocessing since they are in the tin-lead form. This will affect the cost of supporting an all tin-lead assembly. On the other hand, if one wishes to support an all lead-free assembly the legacy parts are already paid for and they must be either reprocessed or discarded thereby affecting the cumulative cost.

Equation (4) adapts to the availability of legacy parts and displays these effects on the plot.

$$f'_{LF_1} = f_{LF_1}\left(1 - f_{LTB}\right)$$
$$f'_{TL_1} = \begin{cases} f_{LTB} + f_{TL_1}\left(1 - f_{LTB}\right) & \text{if legacy parts must be used} \\ f_{TL_1} & \text{if legacy parts are disposed of} \end{cases} \qquad (4)$$

where $f_{LTB}$ is the fraction of parts for which an inventory of legacy tin-lead parts exists. The modified profile starts at the points computed in (4) and rejoins the baseline profile in the fifth year which is when the legacy part inventory is depleted.

From (4), the fraction of parts that are only available as lead-free parts is the fraction of parts that are manufactured only as lead-free for that year minus the legacy tin-lead parts that are not manufactured as tin-lead anymore but the organization owns legacy parts in the tin-lead form. The fraction of parts that are available only as tin-lead is the fraction of parts needed in the year that have been accounted for by the lifetime buy in addition to the fraction of parts only manufactured in the tin-lead form in the year that are not available in the legacy parts. The fraction of parts available as tin-lead or lead-free does not need modifications if the legacy parts are disposed of. It should be kept in mind that in the case of discarding legacy parts, disposal costs must be accounted for in the cost of supporting the product as well as the lost investment in the legacy part inventory.

## Impacts on Sparing

As mentioned before it can be assumed that reprocessing tin-lead parts to lead-free and vice versa or fabrication of mixed tin-lead/lead-free systems has a possible effect on the reliability of the system. This reliability change is accounted for in the number of spares the organization must have to keep their systems operational.

The number of spares required to keep the system running is estimated using the Poisson distribution since the Poisson distribution is a discrete probability distribution that expresses the probability of a number of events occurring in a fixed period of time. The number of events is the failures occurring and is representative of the number of spares that will be required. When the number of spares, k, is large, the Poisson distribution can be approximated by the normal distribution and k becomes a Poisson random variable with mean, $\mu = \sigma^2 = \lambda nt$, where λ is the failure rate and n is the number of parts and t is the time [24]. The sum of Poisson random variables is also Poisson and the mean of the sum equals the sum of the means. Therefore the Poisson random variable k can be thought of as the sum of m random variables Xi with $\mu_x = \sigma_x{}^2 = \frac{\lambda nt}{m}$. The Central Limit Theorem states that the mean of m identically distributed random variables is approximately normal with mean $\mu_x$ and variance $\frac{\sigma_x{}^2}{m}$. This means that $\frac{k}{m} = \frac{\sum_{i=0}^{m} X_i}{m}$ can be approximated with a normal with mean $\mu = \frac{\lambda nt}{m}$ and $\sigma^2 = \frac{\lambda nt}{m^2}$. The test statistic used in this case is the z statistic which is used to test a hypothesis about a population's mean for the normal distribution. Since $z = \frac{x - \mu}{\sigma}$, $x = z\sigma + \mu$. The equation simplifies to $\frac{k}{m} = \frac{z\sigma + \mu}{m}$.

After substituting for μ and σ and solving for z, the equation becomes $\frac{\frac{k}{m} - \frac{n\lambda t}{m}}{\frac{\sqrt{n\lambda t}}{m}} = z$

which simplifies to $\frac{k - n\lambda t}{\sqrt{n\lambda t}} = z$

Solving for k yields (5), which gives the number of spares a system requires,

$$k = \left\lceil n\lambda t + z\sqrt{n\lambda t} \right\rceil \tag{5}$$

where,

k = number of spares
n = number of boards fielded
t = time
λ = failure rate

z = number of standard deviations from the mean of a standard normal distribution, which is a function of the confidence level desired [25].

Statistically, z is known as the normal variant for the α percentile and k is the α% fill rate. Keep in mind that this equation is only applicable when times between failures are exponentially distributed and the repair times are independent and exponentially distributed too. Therefore if the size of parts stock and the failure rate is known and the desired confidence level over the desired time period is also known, (5) can be used to determine the number of spares that must be acquired to maintain that system.

Equation (5) was used in the model to determine the new number of spares required. First, the number of required spares for the conventional tin-lead parts is assumed to be a user defined fraction of the total inventory of parts required to support the tin-lead version of the system, $k_{orig}$. Using a desired confidence level and $k_{orig}$, (5) can be used to obtain the failure rate time product ($\lambda t$) of the tin-lead parts.

In order to find the new number of spares due to the introduction of the lead-free parts, the new failure rate time product is determined using the following process.

The reliability of a part, assuming constant failure rate is

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

where $\lambda$ is the failure rate and t is the time. In the case where there are $N_b$ number of parts, the failure rate becomes

$$R(t) = (e^{-\lambda t})^{N_b}.$$

When the parts are reprocessed the failure rate of the overall board changes and becomes

$$R(t)_{new} = (e^{-\lambda t_{new}})^{N_b}$$

where $\lambda t_{new}$ is the new failure rate term and $N_b$ is the total number of parts on the board.

If $N_{rp}$ parts are reprocessed they will have a failure rate that is different from the other parts on the board that are not reprocessed. The failure rate for the reprocessed parts becomes

$$R_{N_{rp}} = (e^{[-\lambda t_0 (1-M)]})^{N_{rp}}$$

where the term (1-M) denotes the change in failure rate due to reprocessing. The remainder of the parts has the original failure rate given by,

$$R_{N_b - N_{rp}} = (e^{-\lambda t_0})^{N_b - N_{rp}} .$$

The overall reliability of the $N_b$ part system then becomes

$$\begin{aligned}
R(t)_{new} &= R_{N_{rp}} R_{N_b - N_{rp}} \\
R(t)_{new} &= (e^{-\lambda t})^{N_b} (e^{[-\lambda t_0 (1-M)]})^{N_{rp}} \\
(e^{-\lambda t_{new}})^{N_b} &= (e^{-\lambda t})^{N_b} (e^{[-\lambda t_0 (1-M)]})^{N_{rp}}
\end{aligned}$$

Solving for $\lambda t_{new}$ yields the following

$$\begin{aligned}
-\lambda t_{new} N_b &= -\lambda t_0 N_b + \lambda t_0 N_{rp} - \lambda t_0 N_{rp} + \lambda t_0 N_{rp} M \\
-\lambda t_{new} N_b &= -\lambda t_0 (N_b + N_{rp} M)
\end{aligned}$$

And the final equation becomes

$$\lambda t_{new} = -\lambda t_0 (1 + M \frac{N_{rp}}{N_b}) \qquad (6)$$

where,

$\lambda t_0$ = original $\lambda t$ of a <u>part</u> (~original $\lambda t$ of the <u>system</u> divided by $N_b$)
$\lambda t_{new}$ = new effective $\lambda t$ of an average part
$N_b$ = number of parts on a board
$N_{rp}$ = number of reprocessed parts

M = fractional change in failure rate for the reprocessed parts (can be positive or negative), positive denotes and increase in failure rate.

The quantity $n\lambda t_{new}$ reflects the change in the failure rate due to adopting the lead-free parts. One thing to note from (6) is that the term $N_{rp}/N_b$ is the fraction of parts that is available in the form that requires reprocessing. This fraction can be obtained directly from the profile elaborated earlier in Figure 1. The M value is the change in the failure rate and can be manipulated by the user based on their specific data. Notice that the actual values of the failure rates are never needed, only the change in the failure rate, M. The development above is valid for a constant failure rate assumption as expressed in (6) and would also be valid for Weibull failure distributions.

The new failure rate that is determined using (6) can then be plugged back into (5) to determine the new number of spares. The model will then determine the additional number of spares the organization must purchase. The change in the number of spares is given by $\Delta k = k_{new} - k_{orig}$. The cost of the difference in spares is given by (7),

$$C_{spares} = \Delta k\left(N_{rp}C_{rp} + C_{board}\right) \tag{7}$$

where, $C_{board}$ is the cost of procuring a conventional version of the spare board including part costs, assembly, testing, etc. The cost therefore is the additional number of spares times the reprocessing costs of the spares themselves (if needed) and the cost of the new board since the last board was deemed failed and must be replaced.

## Tin Whisker Risk Model

The new lead free tin alloys with their lack of lead content are more susceptible to failure due to the formation of tin whiskers. Whiskers form due to mechanical and thermal stresses and will create short circuits on the board. This added risk of failure is accounted for in the model in the form of additional spares. Tin whisker risk is the probability of a conductive whisker growing across electrically isolated adjacent conductors and creating a short. A bridging short is assumed to occur if the tin whisker has the minimal length and appropriate angle to span the space between the 2 conductors. This can be expressed as

$$l_w.\sin(\theta) \geq l_s$$

where $\theta$ is the whisker growth angle, $l_w$ is the length of the whisker and $l_s$ is the pitch space between 2 conductors [19].

The model requires the user to enter information describing the physical nature of the part. The user has to provide the gap size between leads and the area of the leads. The coating factor which is the percentage of the area (of leads) that is coated with solder is also required. The final input required is the type of tin finish. There are different rates of tin whisker growth for different finishes. The model accommodates a bright tin finish and a matte tin finish. Based on the choice of finish, the means and standard deviations for the length and density of tin whisker formation are determined from presorted data [26]. The next step is to determine the number of tin whiskers for a given part. In order to do this, the whisker density must be determined and this is done using the information about the whisker density mean and whisker density standard deviation and the lognormal distribution [26]. Once the density is determined, the tin whisker count can be obtained by multiplying density by the area designated by the user. The whisker count should be multiplied by the coating factor since only the areas with a tin finish will grow tin whiskers. Once the final whisker count is determined, the lengths of the whiskers can be determined. Similar to the density, the lengths are determined using the information about the means and standard deviations of the length and the lognormal distribution [26]. Once the length of the tin whisker is available, the model starts testing to determine if

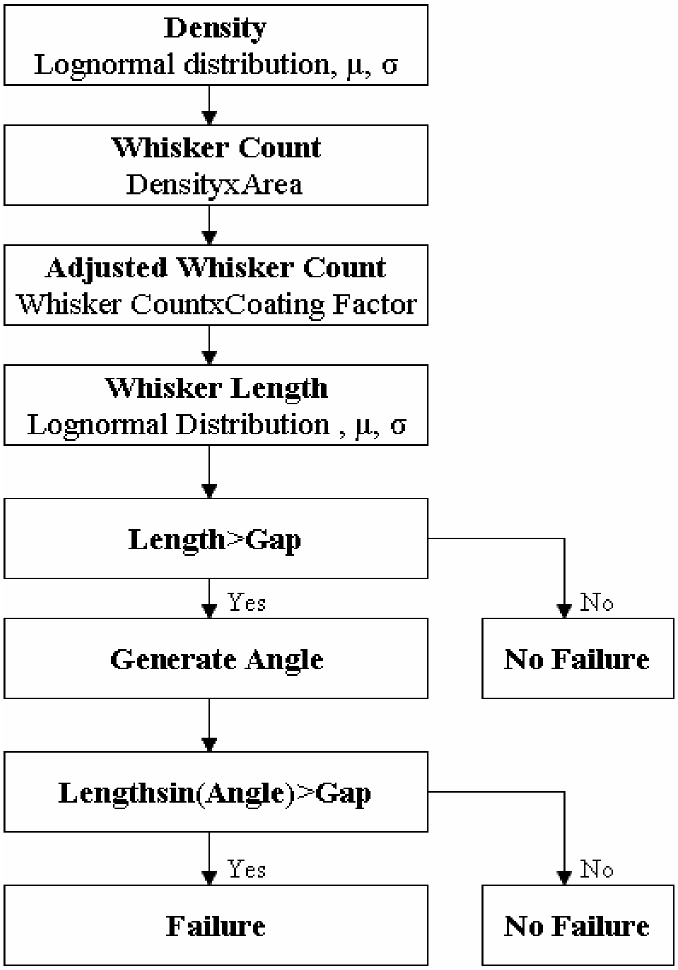


**Figure 3: Flowchart to Determine Tin Whisker Failures**

any of the whiskers will cause a failure. A whisker will cause a failure if it connects two adjacent leads. In order to do this, the whisker length must be longer than the gap length. However, in some cases the tin whisker may grow at an angle that will not precipitate any contact with adjacent leads. In the case that the whisker length is shorter than the gap length, there is no concern for failure. If the whisker length is longer than the gap length, then the model generates a random angle to represent the angle at which the tin whisker is growing. If the length of the whisker multiplied by the sin of this angle is greater than the gap, the whisker causes a failure. These steps are performed in a Monte Carlo loop and the user specifies the number of samples and then the model sums up all the failures and delivers it to the user. Every part that fails must have a spare for its replacement. The sequence of activities is schematically described in Figure 3.

### Plan Implementation and Maintenance

Another effect the model takes into consideration is the plan development and maintenance costs. It can be naturally assumed that developing plans for the transition to lead-free and implementing them will involve several non-recurring and recurring costs. When dealing with this model a ‘plan’ is defined as a unique combination of materials and/or qualification requirements specific to these materials. Therefore plan development costs will include activities such as determining appropriate solders, conducting reliability tests, assembly processes specific to the solder, etc. These costs will increase as the number of plans being developed increases. While developing the plan and implementing it will be a one time cost, maintenance of this plan as explained before will be a yearly recurring cost. In the end, the cost incurred by the company will depend on the number of plans it decides to develop and support yearly. Equation (8) displays the basic costs the model considers as plan implementation and maintenance costs for a given year.

$$C_{plan} = \frac{C_{plan1}}{z_1} + \sum_{k=2}^{n} \frac{(1 - c)C_{plan}}{1} + C_{rp_{NRE}} \tag{8}$$

where,

$C_{plan1}$ = cost of development and implementation of the first plan
$z_1$ = number of years the development and implementation of the first plan is spread over
n = number of plans supported
c = plan commonality (fraction of plan development and implementation cost that can be avoided after the first plan)
$C_{rpNRE}$ = NRE cost associated with reprocessing.

The first term is the one time cost of plan development for the first plan developed spread over the number of years the plan is expected to last. This allows the user to see how much implementing the plan will cost him over the period of years he is concerned with. The second term deals with costs incurred due to all additional plans that are developed. The equation is based on ‘c’ which is described as the commonality between plans. If there are a lot of factors in common between plans such as solder materials, assembly processes etc then it is less expensive for the company to develop the additional plans. For example, a certain solder may have a specific assembly process and if this is already tested and qualified in one of the plans, the next plan that makes the same choices need not qualify the process again. Consequently, if the plans have very little in common, the development cost will be significantly higher. Therefore, the cost of all additional plans is dependent on how many things they have in common with each other. The last term for the plan development equation are the non-recurring engineering costs that may arise.

While (8) gives the cost of development and implementation of plans, (9) gives the cost of plan maintenance. Both of these costs must be accounted for when assimilating the different costs. Costs will be incurred to maintain the plans that have been developed. Therefore it is assumed that a fraction of the development and implementation costs will be needed every year to maintain the plan. This fraction is denoted as $f_m$ in the equation. Some plans may require more maintenance than others, for example some plans may require new tooling every year while some may not. The cost of maintaining all subsequent plans is once again depended on the commonality of the different plans. The more the plans have in common, the less expensive it is for the company to maintain them.

$$C_{\text{plan maint}} = f_m C_{\text{plan}} + \sum_{k=2}^{n} f_m (1 - c) C_{\text{plan}} \tag{9}$$

where

$f_m$ = fraction of a plans development and implementation cost charged per year to maintain the plan

Note, various portions of (8) and (9) may appear in various years within the calculation.

# Chapter 3: Results

This chapter will use the model that was described in Chapter 2 to generate results regarding the costs involved in adapting to the availability of lead-free parts. The sample results will demonstrate the costs incurred for different management scenarios and as a function of changes in failure rate, supporting multiple plans etc.

The model can be customized to provide the user with several different options or action plans and the cumulative costs associated with each of these action plans. In this chapter, 3 different options are compared for the transition to lead-free. These three different options are:

1. **Option 1 (All tin-lead)** - This is the option where all parts used must be tin lead and those parts that are only available as lead-free will be reprocessed to tin-lead. Conventional tin-lead assembly processes will be used.
2. **Option 2 (All lead-free)** - Lead free parts are used and parts only available as tin-lead are reprocessed to lead-free. A complete qualified lead-free assembly process is used to assemble the lead-free parts.
3. **Option 3 (Mixed Assembly)** - Parts are used as they are available (a mix of tin-lead and lead-free) and assembled using tin-lead assembly processes that have been qualified for a mixed set of parts.

One thing to keep in mind is that there will be different assembly processes and material costs for each of these management options. Also, the different effects described in Chapter 2 such as the availability profile and tin whiskers risk will have different impacts on each of the three options. Therefore, plan development and maintenance costs as well as sparing costs will be affected.

## Baseline Case Analysis

To facilitate comparison, a baseline scenario has been created. The basic assumptions for this baseline scenario have been listed in Table 1. Table 1 summarizes information such as the cost of a board, quantity of boards built and reprocessing costs. It also includes development costs for the initial plan and all subsequent plans as well the fraction of the development costs that is required to maintain all of these plans each year. The table also includes the change in failure rate due to reprocessing. It is assumed that pure tin-lead parts and pure lead-free parts have the same reliability and changes in failure rate are due to defects introduced in reprocessing.

**Table 1: Basic assumptions for all options (baseline)**

| | |
|---|---|
| Number of Boards | 24 |
| Parts per Board ($N_b$) | 300 |
| Quantity Built per Year of Each Board | 1000 |
| Cost of Reprocessing Lead-free to Sn-Pb ($C_{rp}$) | \$1 |
| Cost of Reprocessing Sn-Pb to Lead-free ($C_{rp}$) | \$2 |
| Cost of Spare Board ($C_{board}$) | \$10,000 |
| Full Plan Development Cost ($C_{plan1}$) – one plan | \$5,500,000 |
| Plan Maintenance (fraction of $C_{plan1}$) ($f_m$) – one plan | 0.1 |
| Discount Rate (d) | 10% |
| Reprocessing Qualification Cost ($C_{rpNRE}$) | \$1,000,000 |
| Reprocessing Maintenance (fraction of $C_{rpNRE}$) | 0.1 |
| Number of Plans Supported (n) | 1 |
| Fractional Change in Failure Rate Associated with Reprocessing Parts (M) – part level | +0.1 |
| Fractional Change in Failure Rate Associated with Performing Mixed Assembly (M) – board level | +0.15 |

## Cumulative and Annual Costs

The results that will be discussed for the different management scenarios require the same information, failure rate, development cost, plans supported etc, as the baseline case in Table 1. As explained in Chapter 2, the different costs involved are plan development cost, plan maintenance cost, reprocessing costs, sparing cost due to change in reliability and sparing cost due to tin whisker formation. Figure 4 displays the cumulative costs incurred for a period of 10 years for each of the 3 management options. In the figure, the horizontal axis is the year and the vertical axis is the cumulative cost in year 1 dollars. The plot with the open red triangles is Option 1 where all lead-free parts are reprocessed to tin-lead parts and the plot with the closed blue squares is Option 2 where all tin-lead parts are converted to lead-free parts. Option 3 is the data set with the closed red triangles and shows the costs incurred when a mixed assembly is considered.

It can be seen from Figure 4 that initially Option 1, which is reprocessing lead-free to tin lead, is the least expensive plan. This is likely because most parts are still available in the tin lead form, as assumed in Figure 1 in Chapter 2, and there is little reprocessing necessary. Option 2, reprocessing tin-lead to lead-free, is the most expensive in year 1 and year 2 since a majority of the parts is still available only as tin

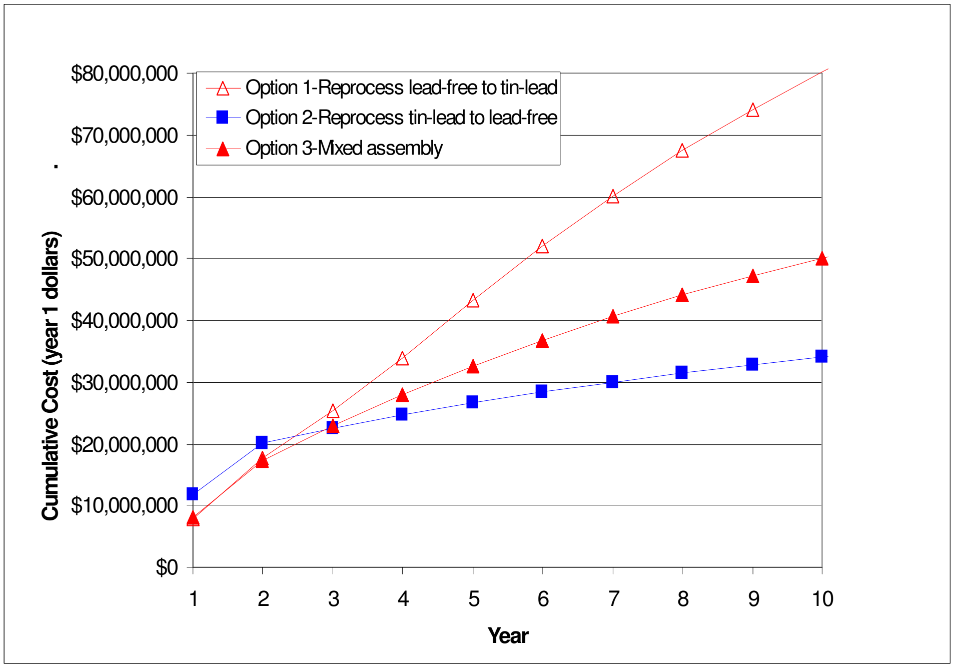


**Figure 4: Cumulative Cost for Baseline Case**

lead and in order to sustain a lead-free system significant reprocessing costs will be incurred. Over the course of the next 10 years it can be seen that the costs involved with each option changes. Option 3, the mixed assembly, which was initially more expensive than Option 1, becomes less expensive than Option 1. The cost for Option 2 starts to decrease relative to Option 1 and Option 3 in year 2. At the end of 10 years Option 2 which started off as the most expensive option, becomes the least expensive. Referring back to the availability profile (Figure 1 in Chapter 2) it can be seen that virtually all parts are available in lead-free form. Therefore Option 2 is very easily operated and sustained at the end of 10 years. The difference in cumulative costs between Option 2 where everything is converted to lead-free and Option 3, the mixed assembly which is the second least expensive option, is around $18 million in year 10. Consequently supporting Option 1, the all tin lead process, is the most expensive due to the eventual unavailability of parts and the significant reprocessing costs as well as sparing costs. Figure 4 is the baseline case that will be compared with all the other results in this Chapter.

It is also of interest to see how the annual costs change over the years as the availability of tin-lead and lead-free parts change. Figure 5 shows the annual costs for the different management plans for 10 years. The vertical axis of the graph is annual costs in year 1 dollars and the horizontal axis is the year. Notice that the cost for year 1 is significantly higher than future years. Also, the one time plan development and implementation cost is incurred in Year 1 but spread out over the next 10 years. Overall the annual cost plots have a negative slope due to the non-zero cost of money (and no inflation was assumed). Once again, initially Option 2 of

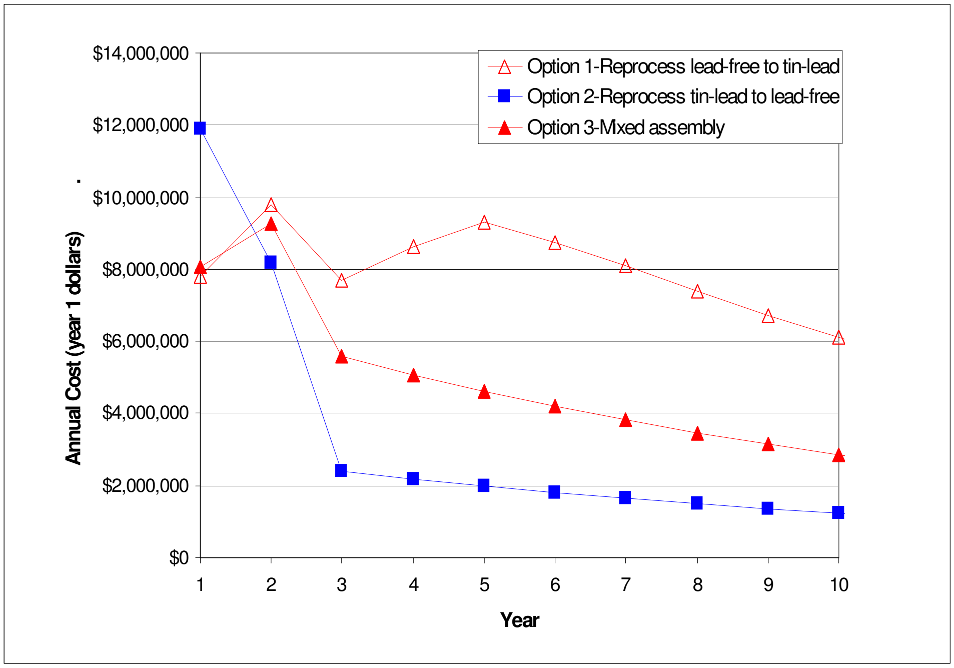


**Figure 5: Annual Cost for Baseline Case**

reprocessing tin-lead to lead-free is the most expensive follow by Option 3, the mixed assembly. Reprocessing lead-free to tin-lead has the cheapest annual cost for the first 2 years. But the graph shows the annual costs for Option 2 and Option 3 quickly trail down over the next few years. In the tenth year, Option 2 of converting to lead free has the smallest annual cost and Option 1 of reprocessing lead-free to tin-lead is the most expensive.

### *Comparison of Sparing and Reprocessing Costs*

Since it is assumed that the differences in costs for the different options are due reprocessing and sparing costs, these costs have been isolated for all the options and the annual contribution of reprocessing and sparing can be clearly seen. Same as in Figure 5, the horizontal axis is the number of years and the y axis is the annual cost in year 1 dollars. Figure 6 shows the reprocessing costs incurred yearly in supporting each of the plans. As expected, Option 1 of reprocessing all parts to tin-lead incurs

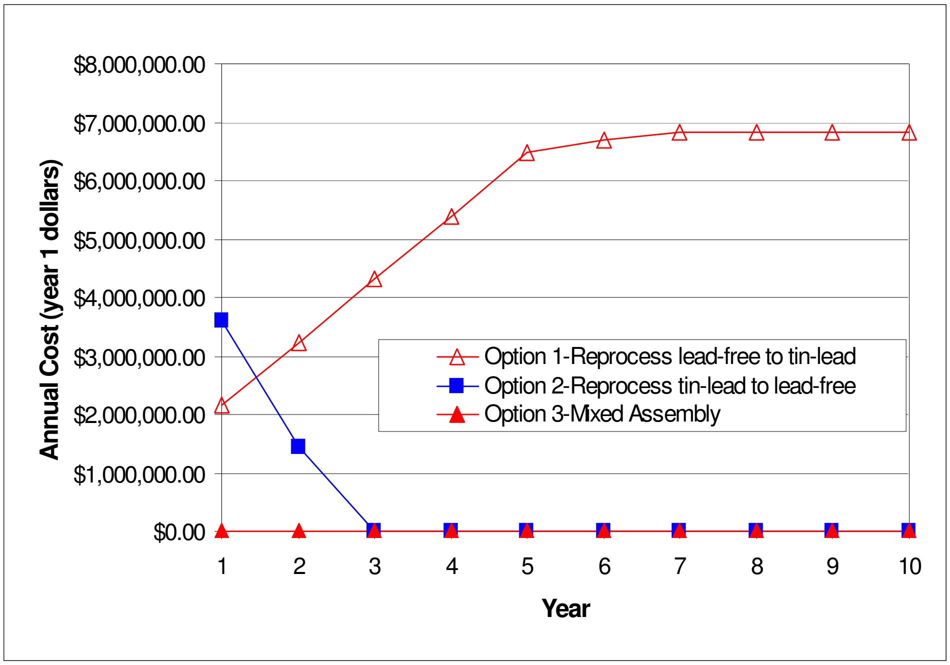


**Figure 6: Comparison of Reprocessing Costs**

the highest reprocessing costs whereas for Option 2 where everything is reprocessed to lead-free reprocessing costs significantly decrease in the course of 10 years. Option 3 with the mixed assembly has no reprocessing costs since parts are used as they become available and there is no reprocessing activity.

Sparing cost due to change in failure rate was also isolated. Figure 7 shows the sparing costs incurred by each of the different management options. The change in failure rate is applied to all lead-free parts. Option 2 and Option 3 have much higher sparing costs since the quantity of lead-free parts is higher. Option 3 is higher in cost since the failure rate increase for the mixed assembly is higher. Option 1 where all parts are reprocessed to tin-lead has lowest sparing costs since it has no lead-free parts.

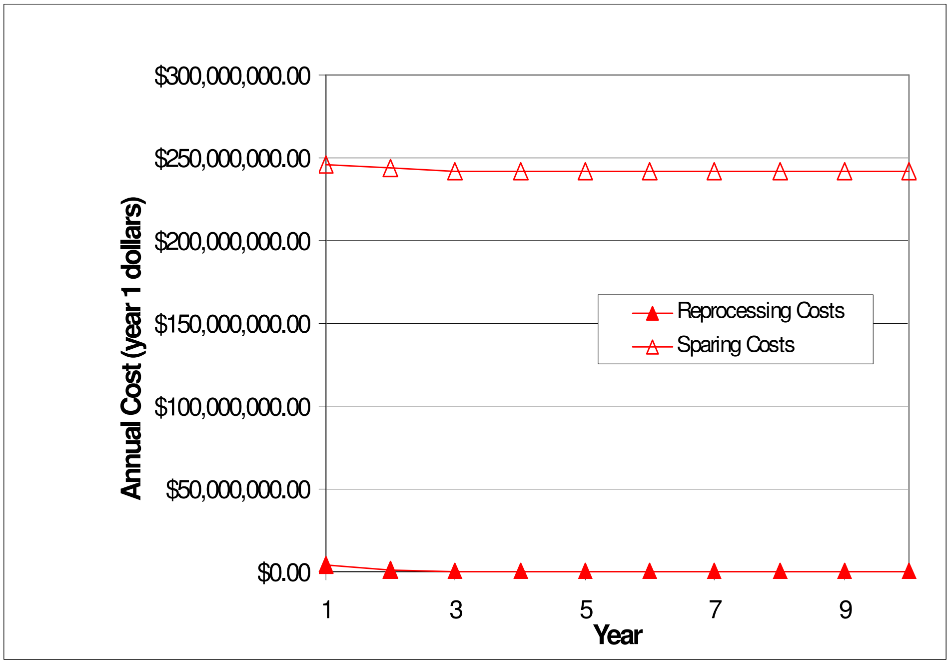


**Figure 7: Option 2 Comparison of Costs**

With the above generalizations in mind, it would be interesting to see what costs dominate for the different plans. For this reason, the annual sparing and

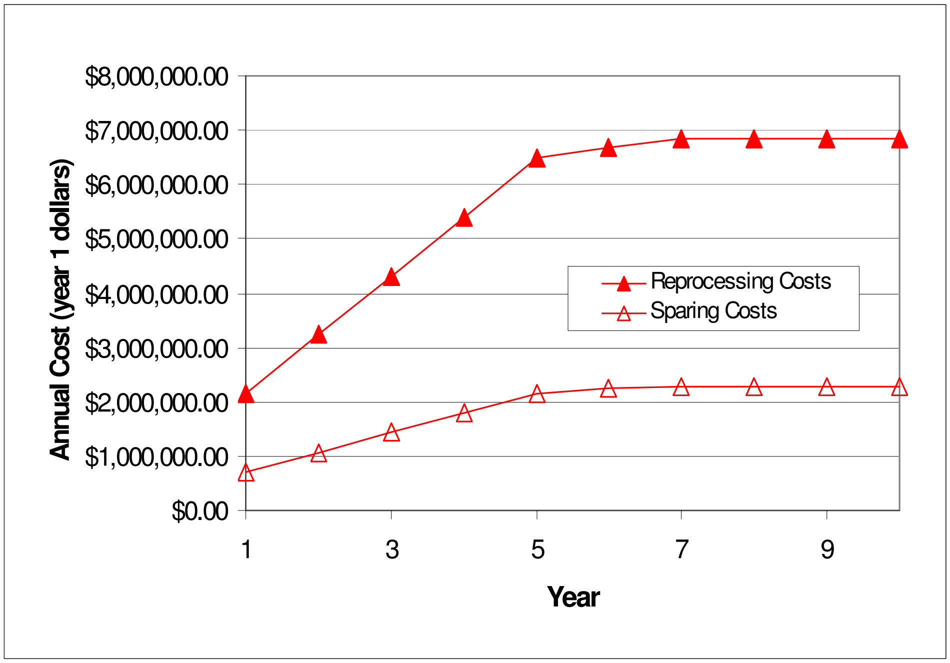


**Figure 8: Option 1 Comparison of Costs**

reprocessing costs were plotted for Option 1 and Option 2. Option 1, the all tin-lead assembly, is the most expensive over 10 years. However, Figure 7 showed that Option 1 has significantly lower sparing costs than Option 2 and Option 3. This must mean the reprocessing costs dominate the sparing costs for Option 1. Figure 8 shows that this indeed is true, reprocessing costs are significantly higher than sparing costs for Option 1.

Option 2 of the all lead-free assembly is the least expensive plan over the 10 years. Figure 9 shows the comparison between the sparing costs and reprocessing costs for the all lead-free assembly. Clearly, sparing costs is significantly higher than reprocessing costs. Reprocessing costs become almost negligible at the end of the 10 years since almost all the parts are available as lead-free parts. On the other hand, since it is assumed that failure rate increases by 10% for the lead-free assembly, the sparing costs is much higher than for the case of Option 1, the all tin-lead assembly.

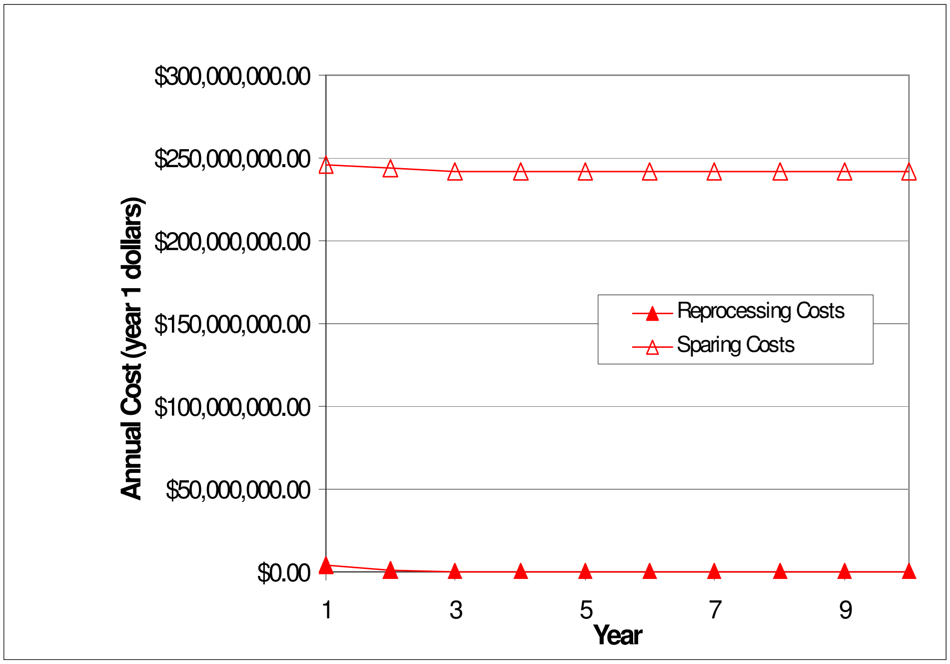


**Figure 9: Option 2 Comparison of Costs**

## Option of No Action

Figure 4 and 5 show the cumulative and annual costs associated with the 3 different management options. It may also be of interest to see the costs that would be incurred if the industry chose to not take any specific steps (as a unified or otherwise entity) to adapt to lead-free. Figure 10 and Figure 11 draws attention to this. Figure 10 is a cumulative cost graph with the horizontal axis showing the years and the vertical axis showing the cumulative cost in year 1 dollars. The graph has the 3 plots for the 3 management options, the same as in Figure 4 but also includes plots for the case where there is RoHS regulation as well as if the industry chose to not do anything about the reduced availability of tin-lead parts. The least costly data set in Figure 10 (closed green triangles) represents the scenario when there is no RoHS in effect and tin-lead parts are available forever. The cost in this case is not zero since it

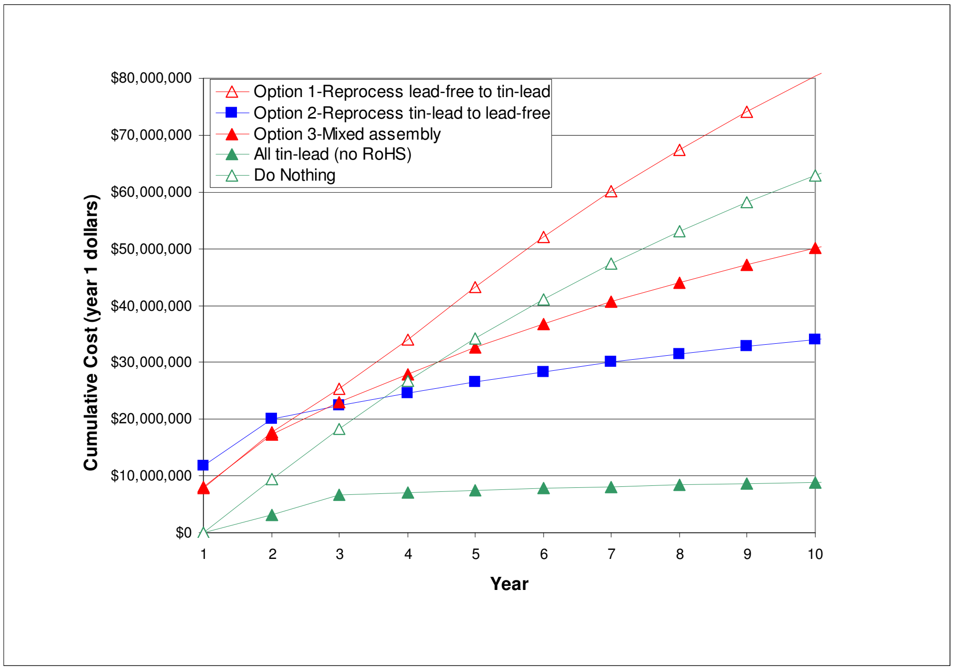


**Figure 10: Cost Impact of Do Nothing Option for 24000 boards**

includes the cost of development and maintenance for 1 plan. However, there are no reprocessing costs or additional sparing costs since nothing changes. The "Do Nothing" option in Figure 10 is different from the mixed assembly option (Option 3). In Option 3, the assembly processes have been qualified for a mixture of tin-lead and lead-free parts. In the case of the Do Nothing option, the same conventional assembly processes are being used despite the parts having changed, i.e., the existence of lead-free parts is being ignored by the assembly process. This will increase the failure rate. The data in Figures 10 and 11 were generated assuming a 30% increase in failure rate for the Do Nothing Option. Figure 10 is the case where 24,000 boards are being manufactured and Figure 11 is for when only 4,800 boards are being manufactured.

Clearly, for both Figure 10 and Figure 11, the option for an all tin-lead assembly with no RoHS ban is the least expensive. This is because the companies

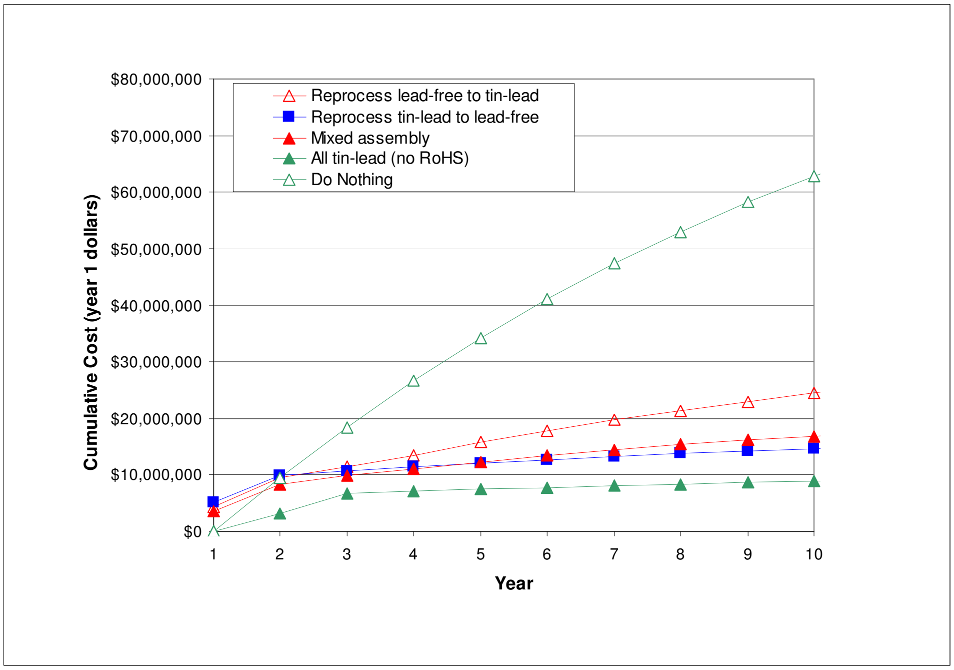


**Figure 11: Cost Impact of Do Nothing Option for 4800 boards**

can continue using tin-lead parts as they have in the past since they will not become unavailable due to replacement with lead-free parts. Nothing changes for the suppliers and the consumers. Therefore, there is also no initial plan development and implementation costs either. The second least expensive option is Option 2. As explained before, this is the least expensive option when the RoHS regulations are in place. The third least expensive option for both the cases is Option 3, the mixed assembly. For the case where 24,000 boards are being manufactured, the most expensive option continues to be Option 1 with the all tin-lead assembly. Interestingly, the option of mixed assembly is much cheaper than choosing not to take any definitive action. For the case of 4,800 boards however, at the end of 10 years, Option 1 of sustaining an all-tin assembly is much less expensive than failing to take action. If the industry chose not to do anything about the fact that the parts that are available now are different and continued to use them in the same conventional manner (i.e., assembling a mix of tin-lead and lead-free parts using a conventional tin-lead process), the cumulative cost will rise significantly. This is because there will be a lot of failures since the new parts have not been tested and appropriate assembly and maintenance processes have not been qualified for them. This is the reasoning behind assuming the 30% increase in failure rate for the Do Nothing option. While initially it incurs zero plan development and implementation costs, it ends up becoming very expensive to just use parts as they come in. The 3 baseline options all have significant start up costs but the cumulative costs over the 10 year period is significantly lower than doing nothing since preventive actions such as testing the parts for reliability and qualifying all process will be taken.

## Variations in Board Quantities

The previous section showed how the option of Do Nothing shows different results for different board quantities. Of course, a smaller company will incur different costs than a larger industry since they manufacture a different quantity of boards per year. Figure 4 shows the predicted behavior of the management options when different quantities of boards are considered as compared to the 24,000 boards per year in the baseline case (calculated from data in Table 1). Figure 12 represents a smaller manufacturer that only produces 4800 boards in a year. The difference in cumulative cost at the end of 10 years between Option 2 and Option 3, the two cheaper options is $3 million. The same cost difference for the baseline case was $18 million (see Figure 4). Therefore, the difference in costs between a smaller client with 4,800 boards and a larger client 24,000 boards per year is 15 million dollars.

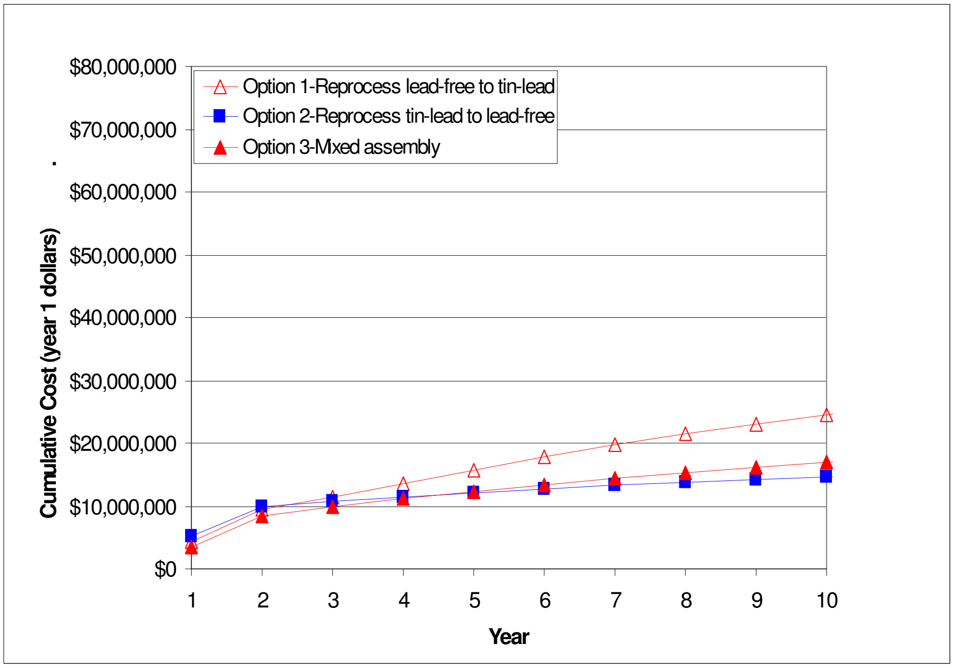


Figure 12: Cumulative Cost for Smaller Board Quantity (same scale as baseline case)

## Cost Effect of Change in Reliability

Since Option 1 and Option 2 incorporate either the use of the new lead-free parts or the reprocessing of parts from tin-lead to lead-free and vice versa, it can be assumed that there could be changes in the failure rate of the board due to the new parts. Table 1 assumes a 10% increase in failure rate of the parts due to reprocessing and a 15% increase in the failure rate of the board when dealing with mixed assemblies. An increase in the failure of the parts and boards requires an increase in the number of spare boards and parts. This will increase the cumulative costs incurred by the manufacturer. Figure 4 showed the baseline case that incorporated the 10% increase in failure rate for Option 1 and Option 2 and the 15% increase in the failure rate for Option 3. Figure 13 shows the case when it is assumed that there is no change in failure rate. The 3 management options start off with the same costs due to

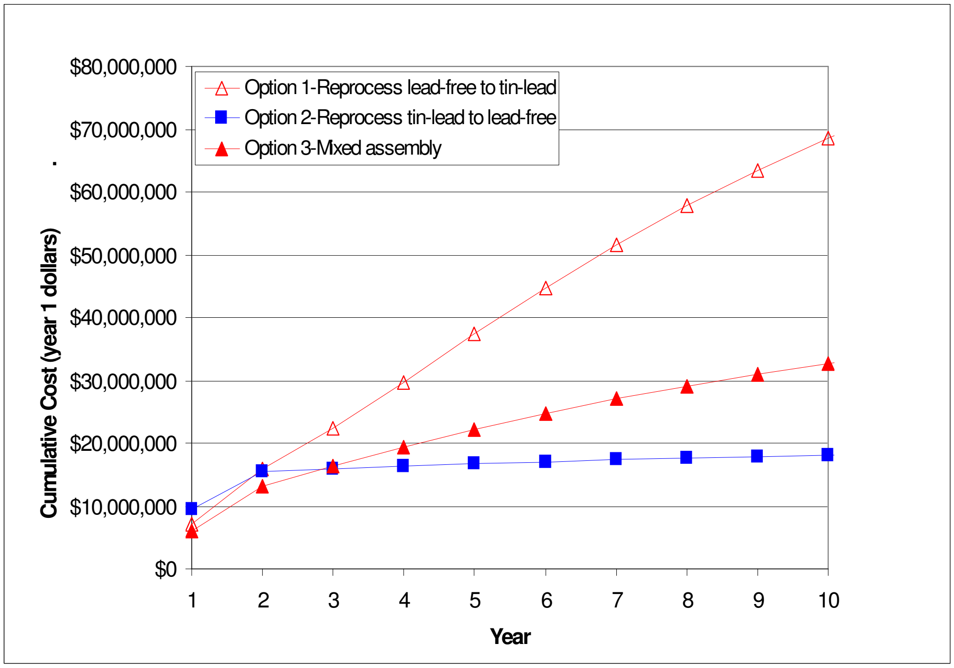


Figure 13: Cumulative Cost for No Change in Failure Rate

plan development and maintenance but at the end of 10 years, it can be seen that Option 3 of the mixed assembly is the least expensive option. This is because, with no change in failure rate, Option 3 incurs neither reprocessing costs nor sparing costs associated with reprocessing. In the baseline case, Option 3 was more expensive than Option 2 since it had a higher failure rate due to the use of mixed parts and conventional tin-lead assembly processes. Option 1 of reprocessing lead-free parts to tin-lead is the most expensive option because while the sparing costs may have been knocked off, the reprocessing costs are still significantly higher since most parts are not naturally available as tin-lead anymore.

### Tin Whisker Risk

Since the new alloys do not contain lead, there is the risk of formation of tin whiskers. The tin whiskers can cause failures that would require more spares. Figure 14 shows the effect of tin whisker risk on the cumulative cost. The two plots on the top of the graph are Option 2 and Option 3 when the distance between the conductors is 0.01 mm. The middle plots are for a gap size of 0.05 mm and the plots at the bottom are the baseline cases (same as those in Figure 4) with no tin whisker risk included. It can be seen that cumulative cost incurred over 10 years is significantly higher when taking tin whisker risk into consideration. This because more spares will be needed to support the system. It can be seen with gap size of 0.05 mm that the first 4 years there is no tin whisker failures but the cost rises significantly after 4 years. Note, these results are completely dependent on the date (year) at which tin-whiskers grow long enough to bridge the gap between adjacent leads and this depends on the length distribution assumed for the whiskers, which is not well known.

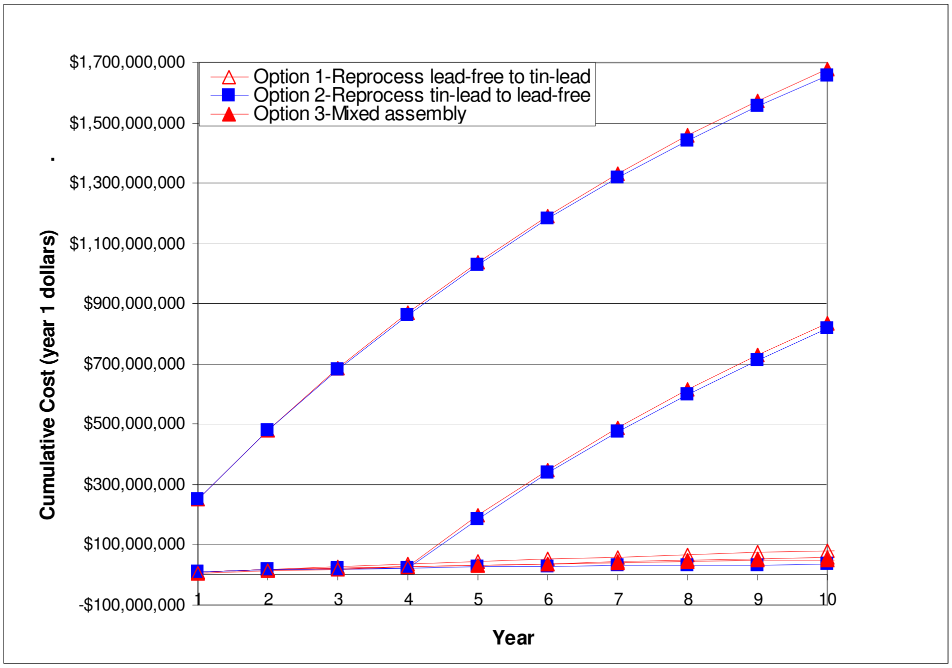


Figure 14: Cumulative Cost with Tin Whisker Risk

Therefore, Figure 14 is included only to demonstrate how costs could escalate if due to tin whisker effects. Also note that this model considers the cost of tin whisker failures to only be the cost of purchasing additional spares and does not consider the other financial consequences of failures do to tin whiskers.

## Cost for Multiple Plans

The baseline case reported the cumulative costs incurred when there was only one plan involved. It has been discussed before that costs incurred for multiple plans will be significantly different. These costs depend on the number of plans as well as the commonality between the different plans. Once again, the word ‘plan’ is used to describe a specific set of materials and/or qualification requirements. Commonality is described as the fraction of these materials and/or qualifications the plans have in common with the first plan that was developed and implemented. Figure 4 showed the costs incurred when only 1 plan was being supported. The cumulative cost at the

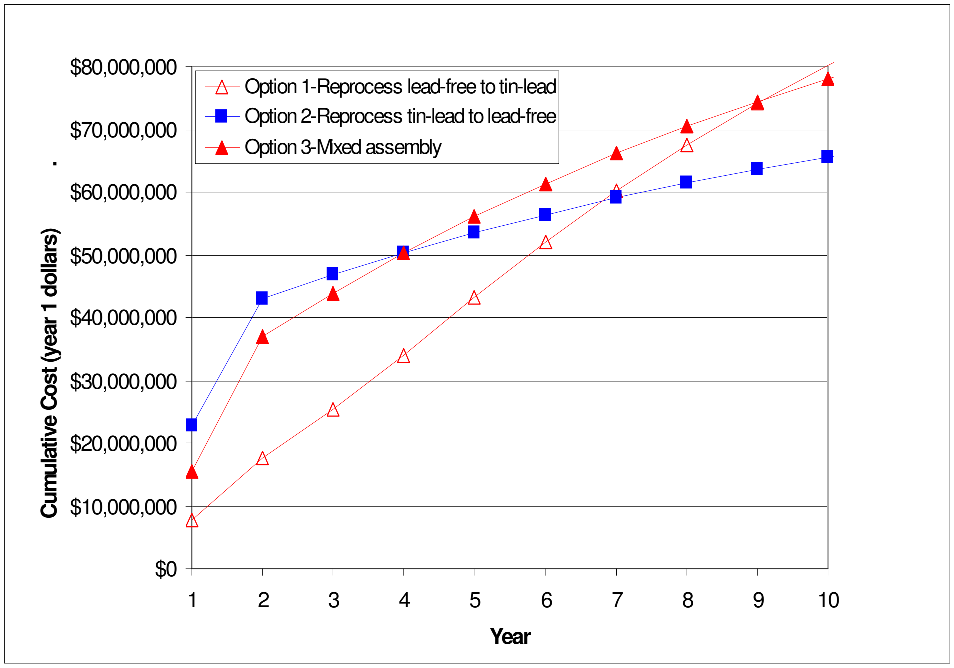


**Figure 15: Cumulative Cost for 10 Plans**

end of 10 years for the least expensive plan was $31 million. Figure 15 shows the difference in behavior when there is more than 1 plan being supported. The graph displays the cumulative costs involved when there are 10 plans to support with an assumed 65% commonality. Since a plan has been described as the unique set of materials and/or qualifications, it is understandably significantly more expensive to support 10 plans. That is 9 more plans that must be qualified than the baseline case and only 65% of the effort (cost) spent on the first plan applies to the subsequent plans. Option 2 which was the least expensive option of reprocessing everything to lead-free has a 10 year cumulative cost of $31 million for the baseline case but the same option has a cost of $62 million when 10 plans have to be supported. In other words, an expense of $31 million could possibly be avoided by having a common plan that is agreed upon by all parties involved.

## Cost Effect of Plan Commonality

Figure 13 displayed how supporting multiple plans is a very expensive endeavor. Figures 16 and Figure 17 further explores the idea of lower costs incurred when supporting fewer plans. The vertical axis of the graphs is the cumulative cost in year1 dollars and the horizontal axis is the number of plans being supported. The two different scenarios investigated are when the 10 different plans have 40% commonality and 90% commonality for the mixed assembly solution. The solid red triangles represent 40% commonality and the open red triangles represent 90% commonality between plans. From the previous section, commonality is a measure of how much each plan has in common with the other plans. Figure 16 shows the costs incurred when $5.5 million as reported in Table 1 is being spent per plan and Figure 17 displays costs when $18.5 million is being spent per plan. It can be seen that

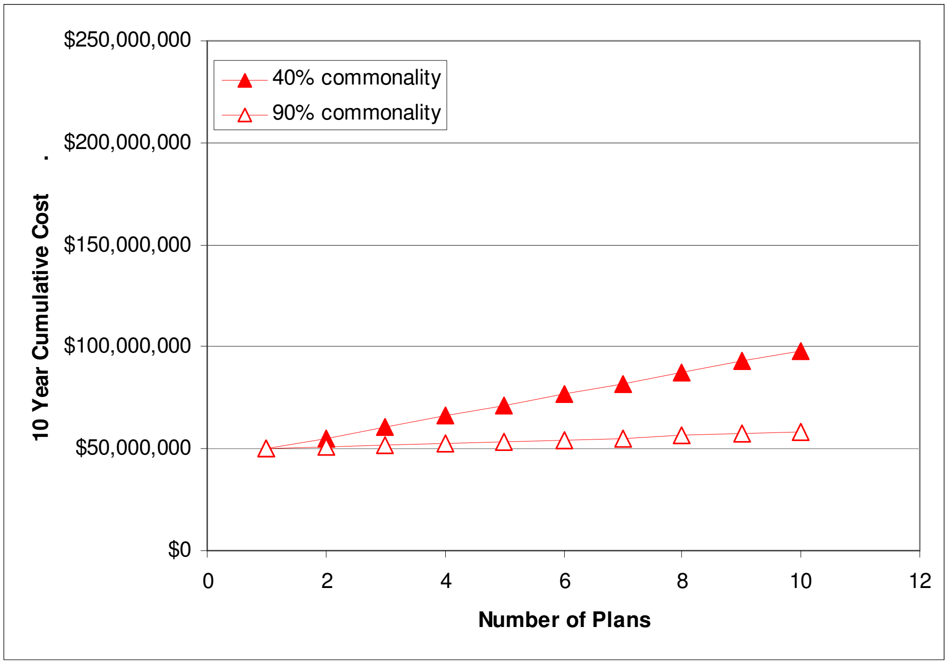


**Figure 16: NRE & Requalification Cost = $5.5M**

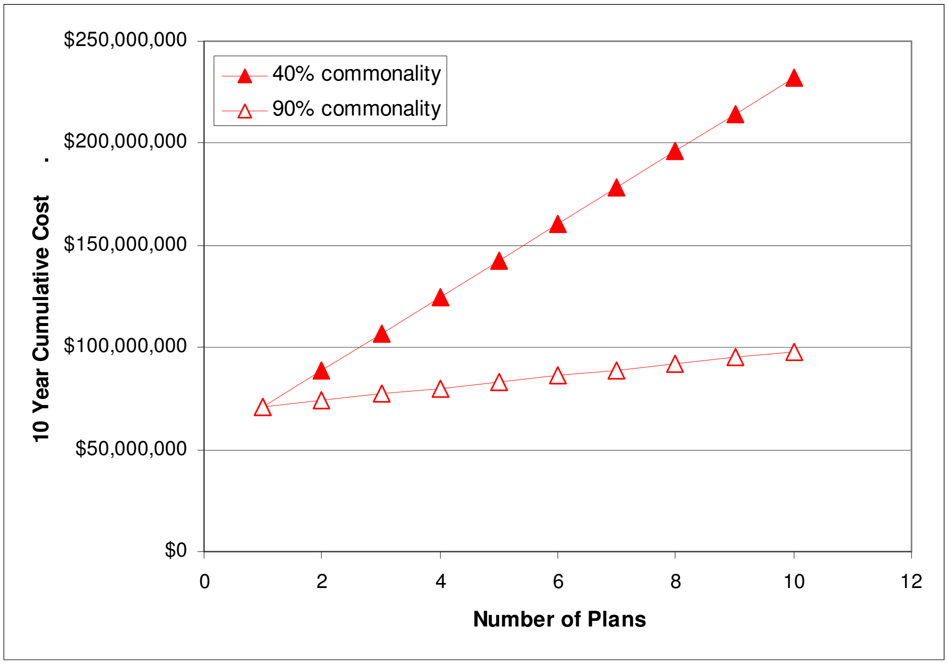


**Figure 17: NRE & Requalification Cost = $18.5M**

cumulative costs are much lower when the plans have a 90% commonality. This is because all the things that the plans have in common need not be tested, developed or qualified more than once. The difference in cost between supporting 10 plans and supporting 1 plan with an estimated spending of $5.5 million per plan and with a 40% commonality is $48 million. The same case for 90% commonality is $8 million. The difference in cost with $18.5 million spent per plan and 40% commonality is $161 million. The same difference for 90% commonality is $27 million. Clearly, if adopting multiple plans, it is more efficient if they have higher commonality.

## Costs due to Legacy Parts

The concept of legacy parts was discussed in Chapter 2. Legacy parts will affect costs whether or not they are used since the cost has already been incurred in purchasing them and in the case of not using them, the money spent on them and their disposal costs will have to be taken into account. For this example is it assumed that in general clients have lifetime buys for 30% of their parts for a period of 5 years and that they are going to utilize the lifetime buy (i.e., use the parts rather than dispose of them). Figure 18 shows the effect of using legacy parts on the cumulative costs for the 3 different options. It should be kept in mind that the lifetime buys will all be in the conventional tin lead form. Therefore initially Option 1 where everything is converted to tin lead starts off as the least expensive since 30% of its parts need not be converted since there is a lifetime buy for them in the inventory. This reduces reprocessing costs as well as sparing costs since the same type of part is being used. For the same reason, Option 2 where everything is converted to lead-free is significantly more expensive since the lifetime buys that are in the tin-lead form will have to be reprocessed. The effect of the legacy parts on Option 1 and Option 2 is very clear in the first 5 years, i.e., the period of years there are legacy parts for. For the first 5 years, Option 2 is the most expensive since the organization decided to use

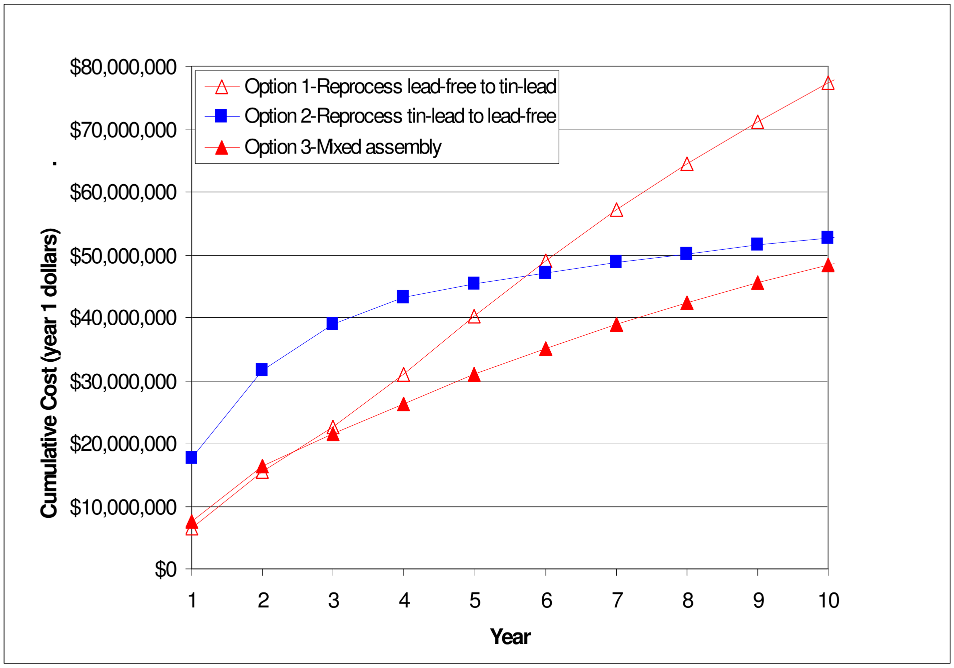


**Figure 18: Cumulative Costs with legacy parts**

the legacy parts and everything has to be converted to lead-free. Option 1 is the least expensive for the first 5 years since the reprocessing costs are lowered. Option 3 for mixed assembly continues to use parts as they are available either in the lead-free form or the tin-lead form. After 5 years however the trends switch since the inventory of legacy parts are depleted. Now converting all parts to lead-free is less expensive since, based on the availability profile, more parts exist in the lead-free form instead of the tin-lead form and minimal reprocessing is required. Option 1of converting everything to tin-lead still comes out as having the highest cumulative cost over 10 years. The difference in cost between Option 1 and Option 2 is significantly lower than in the baseline case where no legacy parts were assumed.

# Chapter 4: Summary Contributions, and Future Work

## Summary

With legislation such as the Regulation of Hazardous Substances (RoHS) and Waste of Electronic and Electrical Equipment (WEEE) in effect and other similar legislation pending around the world, substances such as lead are becoming heavily regulated in consumer products. While the defense and aerospace industries are currently exempt from these regulations because of the nature of their applications, they are still significantly affected due to their reliance on the same supply chain for their parts as consumer applications. The electronic part supply chain is entirely driven by market forces from the consumer sector. This is forcing the defense and aerospace industries to consider alternatives to adapt to the changing availability of conventional tin-lead solder parts. Such an action carries with it significant cost and risk impacts. Defense and aerospace operations require high reliability and have a very long application support time (on the order of decades). It is therefore necessary to qualify all new products to maintain required reliability and performance levels. Consequently, simply incorporating new parts is not easy and requires significant financial resources.

A cost model was created to provide a financial forecast for the transition to lead-free parts. The model includes plan development and implementation costs, reprocessing cost and accounts for changes in reliability due to reprocessing and tin whisker risk through sparing. Example cases considered provided the user with three different options. The first option is an all tin-lead assembly where all parts used are tin-lead and those parts only available as lead-free are converted to tin-lead. The second option is an all lead-free option where all parts are lead-free and those only available as tin-lead are converted to lead-free. The third option is a mixed assembly option where parts are used in whatever form they are available and are assembled using conventional tin-lead processes. Results were generated for different scenarios such as different board quantities, changing failure rate and implementation of multiple plans.

The results of the study indicate that higher board quantity as well as increase in failure rate increased costs. However, the number of plans being supported is also a huge cost driver. For every plan being supported, there are significant development, implementation and maintenance costs. Costs incurred are less expensive if there is commonality between multiple supported plans. Supporting 10 plans with 90% commonality is much less expensive than supporting 10 plans with 40% commonality. The difference in cost, when $18.5 million is spent per plan, between supporting 10 plans and 1 plan with 40% commonality is 161 million. For the same scenario with 90% commonality, the difference is $27 million. Clearly, it would be least expensive to support only 1 plan across the all the customers. It is advisable for the defense and aerospace industries to adopt a standard plan to deal with this transition to lead-free. This plan can be communicated to all stakeholders as well as the suppliers and significant costs that would normally be shouldered by the defense and aerospace industries can be avoided.

## Contributions

- First cost model addressing the transition from tin-lead to lead-free electronics.
- First study to quantify the value of coordinating transition plans amongst multiple customers.
- Developed novel method of calculating relative costs based on changes in quantities as opposed to the absolute value of the quantities.

## Future Work

The cost model developed in this thesis can be developed further to include more details about the parts and boards, thus improving the accuracy of the cost predictions. Palesko [22] classified costs incurred as components cost, processing costs, yield costs and material costs. Palesko determined that for different board sizes, different types of cost dominate and in boards with very high component costs, assembly costs are most heavily impacted regardless of board size. Keeping these generalizations in mind, it would be beneficial to include details such as board size, board density, assembly yield rates as well as part specifics such as failure rate into the model. This way the user can be provided with a detailed breakdown of costs that will help them figure out what processes or parts need to be improved to reduce costs.

# Appendix: Running the Model

This appendix will guide the user through using the tool. The inputs and outputs will be explained in detail as well as the three different options being investigated.

This application is for use with Excel (developed using Microsoft Office Excel 2003). The spreadsheet uses Macros that must be enabled. You can enable the Macros buy opening Excel and selecting Tools->Options…, Security tab, Macro Security…, choose Medium (or Low); restart the spreadsheet (select "Enable Macros" in the Security Warning if asked).

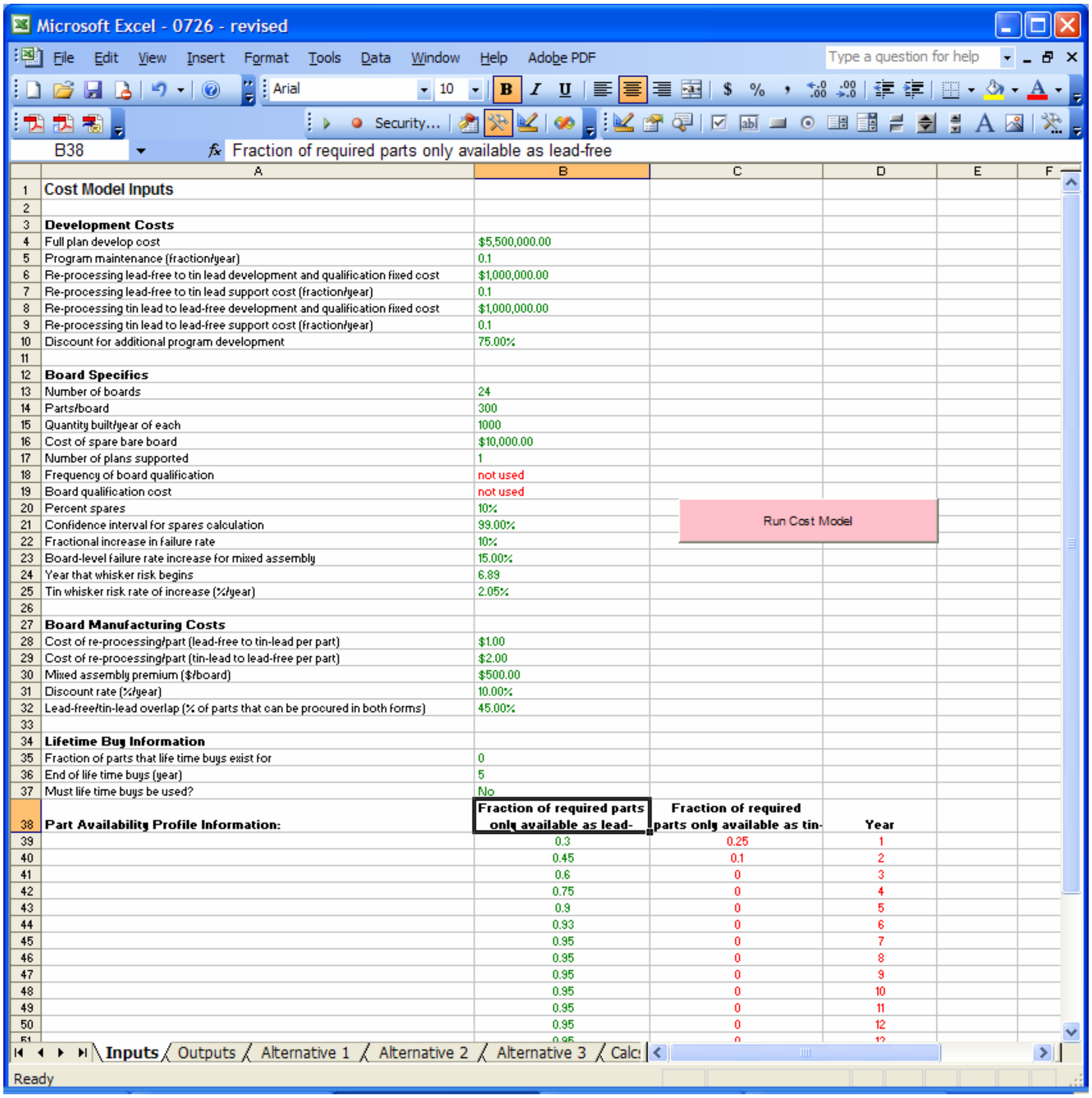
## Reference

### Inputs

The *Inputs* worksheet contains all the model. The table below lists all the inputs the model will use to predict the costs involved in transitioning from tin-lead to lead-free parts. Changes made in the following inputs can be observed as change in the annual and cumulative costs presented in the *Outputs* worksheet.

| **Development Costs** | |
|---|---|
| **Full plan development cost** | Cost associated with developing and implementing one unique combination of materials and/or qualification requirements. |
| **Program maintenance (fraction/year)** | Fraction of full plan development cost required to maintain one plan each year. |
| **Re-processing lead-free to tin lead development and qualification fixed cost** | Cost associated with the development and qualification of a tin-lead to lead-free reprocessing activity. |
| **Re-processing lead-free to tin lead support cost (fraction/year)** | Fraction of the development cost needed to support the lead-free to tin-lead conversion plan each year. |
| **Re-processing tin lead to lead-free development and qualification fixed cost** | Cost associated with the development and qualification of a lead-free to tin-lead reprocessing activity. |
| **Re-processing tin lead to lead-free** | Fraction of the development cost needed to support the tin-lead to |

| | |
|---|---|
| **support cost (fraction/year)** | lead-free conversion plan each year. |
| **Discount for additional program development** | Fraction of cost discounted from full plan development cost for each additional plan developed, e.g., 100% means that additional plan development is free. |
| | |
| **Board Specifics** | |
| **Number of boards** | Number of unique boards manufactured each year. |
| **Parts/board** | Number of parts on each board. This version of the model assumes that every part on the board is the same. |
| **Quantity built/year of each** | Quantity of each unique board manufactured each year. |
| **Cost of spare bare board** | Cost of the bare board that includes all costs except the reprocessing cost of parts. |
| **Number of plans supported** | Number of unique combinations of materials and/or qualification requirements supported. |
| **Frequency of board qualification** | Not used. |
| **Board qualification cost** | Not used. |
| **Percent spares** | Fraction of total boards that are built for spares. |
| **Confidence interval for spares calculation** | Desired confidence level that sufficient spares are available. |
| **Fractional increase in failure rate** | Increase in part failure rate due to reprocessing of parts (if negative, it corresponds to a decrease in failure rate). |
| **Board-level failure rate increase for mixed assembly** | Increase in board failure rate when supporting a mixed assembly (if negative, it corresponds to a decrease in failure rate).. |
| **Year that whisker risk begins** | Year (measured from year 0) when tin whisker risk formation begins and must be accounted for in estimating failures. |
| **Tin whisker risk rate of increase** | Rate at which the number of tin whisker failures increase each year after the first year that whisker formation begins. |
| | |
| **Board Manufacturing Costs** | |
| **Cost of re-processing/part (lead-free to tin-lead per part)** | Cost of reprocessing one part from lead-free to tin-lead. |
| **Cost of re-processing/part (tin-lead to lead-free per part)** | Cost of reprocessing one part from tin-lead to lead-free. |
| **Mixed assembly premium ($/board)** | Additional cost per board to support a mixed assembly. |
| **Discount rate (%/year)** | Discount rate for money. All results are in year 1 dollars. |
| **Lead-free/tin-lead overlap (% of parts that can be procured in both forms)** | Fraction of parts that can be procured in both the tin-lead and lead-free form. |
| | |
| **Lifetime Buy Information** | |
| **Fraction of parts that lifetime buys exist for** | Fraction of parts for which lifetime buys exist in the inventory. |
| **End of lifetime buys (year)** | Number of years the lifetime buy supports after which the parts will have to be purchased again or replaced. |
| **Must lifetime buys be used?** | Choose whether the existing lifetime buys will be used or discarded. |
| | |
| **Part Availability Profile Information** | |
| **Fraction of required parts only available as lead-free** | The fraction of parts only available in the lead-free format can be entered as a function of year for years 1-20 |



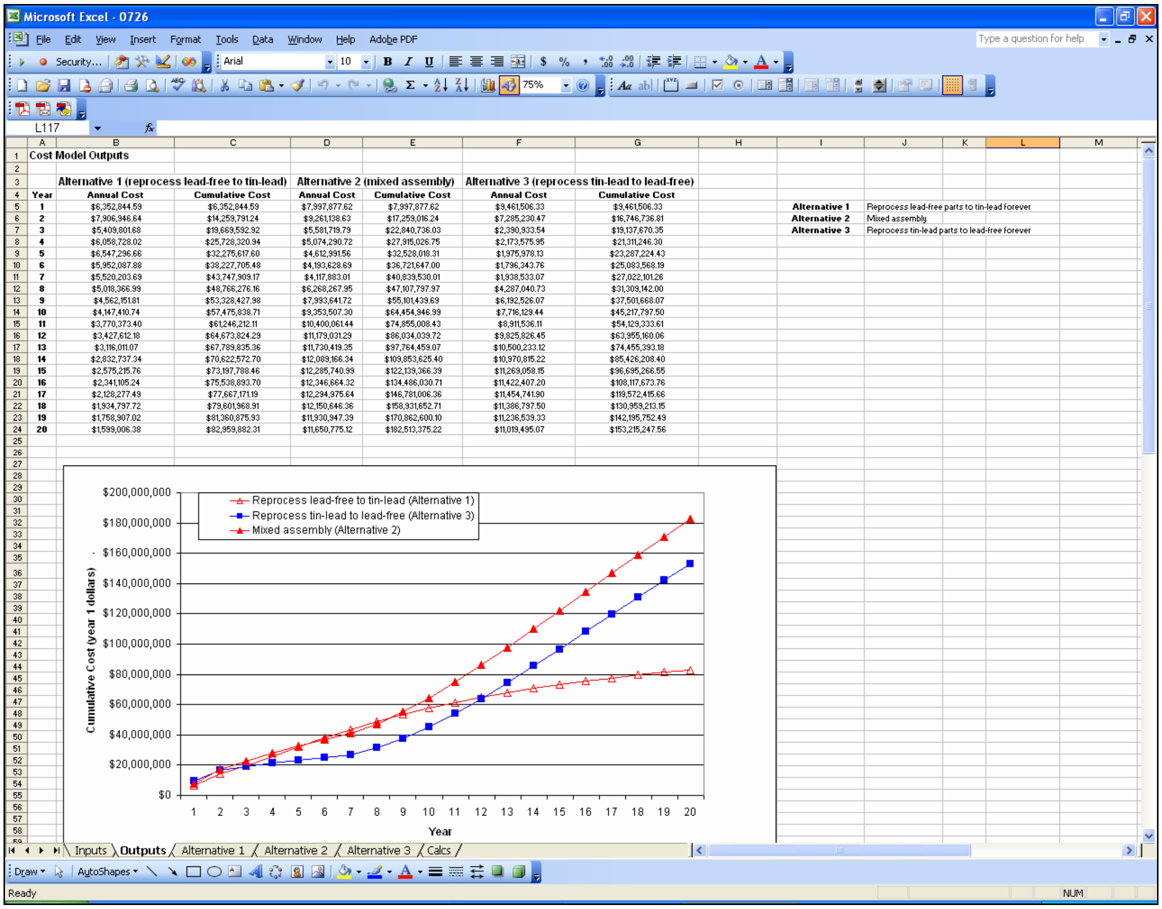
B38 — Fraction of required parts only available as lead-free

| | A | B | C | D |
|---|---|---|---|---|
| 1 | Cost Model Inputs | | | |
| 2 | | | | |
| 3 | **Development Costs** | | | |
| 4 | Full plan develop cost | $5,500,000.00 | | |
| 5 | Program maintenance (fraction/year) | 0.1 | | |
| 6 | Re-processing lead-free to tin lead development and qualification fixed cost | $1,000,000.00 | | |
| 7 | Re-processing lead-free to tin lead support cost (fraction/year) | 0.1 | | |
| 8 | Re-processing tin lead to lead-free development and qualification fixed cost | $1,000,000.00 | | |
| 9 | Re-processing tin lead to lead-free support cost (fraction/year) | 0.1 | | |
| 10 | Discount for additional program development | 75.00% | | |
| 11 | | | | |
| 12 | **Board Specifics** | | | |
| 13 | Number of boards | 24 | | |
| 14 | Parts/board | 300 | | |
| 15 | Quantity built/year of each | 1000 | | |
| 16 | Cost of spare bare board | $10,000.00 | | |
| 17 | Number of plans supported | 1 | | |
| 18 | Frequency of board qualification | not used | | |
| 19 | Board qualification cost | not used | | |
| 20 | Percent spares | 10% | | |
| 21 | Confidence interval for spares calculation | 99.00% | | |
| 22 | Fractional increase in failure rate | 10% | | |
| 23 | Board-level failure rate increase for mixed assembly | 15.00% | | |
| 24 | Year that whisker risk begins | 6.89 | | |
| 25 | Tin whisker risk rate of increase (%/year) | 2.05% | | |
| 26 | | | | |
| 27 | **Board Manufacturing Costs** | | | |
| 28 | Cost of re-processing/part (lead-free to tin-lead per part) | $1.00 | | |
| 29 | Cost of re-processing/part (tin-lead to lead-free per part) | $2.00 | | |
| 30 | Mixed assembly premium ($/board) | $500.00 | | |
| 31 | Discount rate (%/year) | 10.00% | | |
| 32 | Lead-free/tin-lead overlap (% of parts that can be procured in both forms) | 45.00% | | |
| 33 | | | | |
| 34 | **Lifetime Buy Information** | | | |
| 35 | Fraction of parts that life time buys exist for | 0 | | |
| 36 | End of life time buys (year) | 5 | | |
| 37 | Must life time buys be used? | No | | |
| 38 | **Part Availability Profile Information:** | **Fraction of required parts only available as lead-** | **Fraction of required parts only available as tin-** | **Year** |
| 39 | | 0.3 | 0.25 | 1 |
| 40 | | 0.45 | 0.1 | 2 |
| 41 | | 0.6 | 0 | 3 |
| 42 | | 0.75 | 0 | 4 |
| 43 | | 0.9 | 0 | 5 |
| 44 | | 0.93 | 0 | 6 |
| 45 | | 0.95 | 0 | 7 |
| 46 | | 0.95 | 0 | 8 |
| 47 | | 0.95 | 0 | 9 |
| 48 | | 0.95 | 0 | 10 |
| 49 | | 0.95 | 0 | 11 |
| 50 | | 0.95 | 0 | 12 |

**Figure 1 – *Inputs* sheet containing default data.**

### *Outputs*

The *Outputs* worksheet contains the results of the cost model. The annual costs and cumulative costs for the three different options are presented in a tabular form as well as graphical form. All outputs are presented in year 1 dollars. The three models contained within the tool are defined in the following:



**Cost Model Outputs**

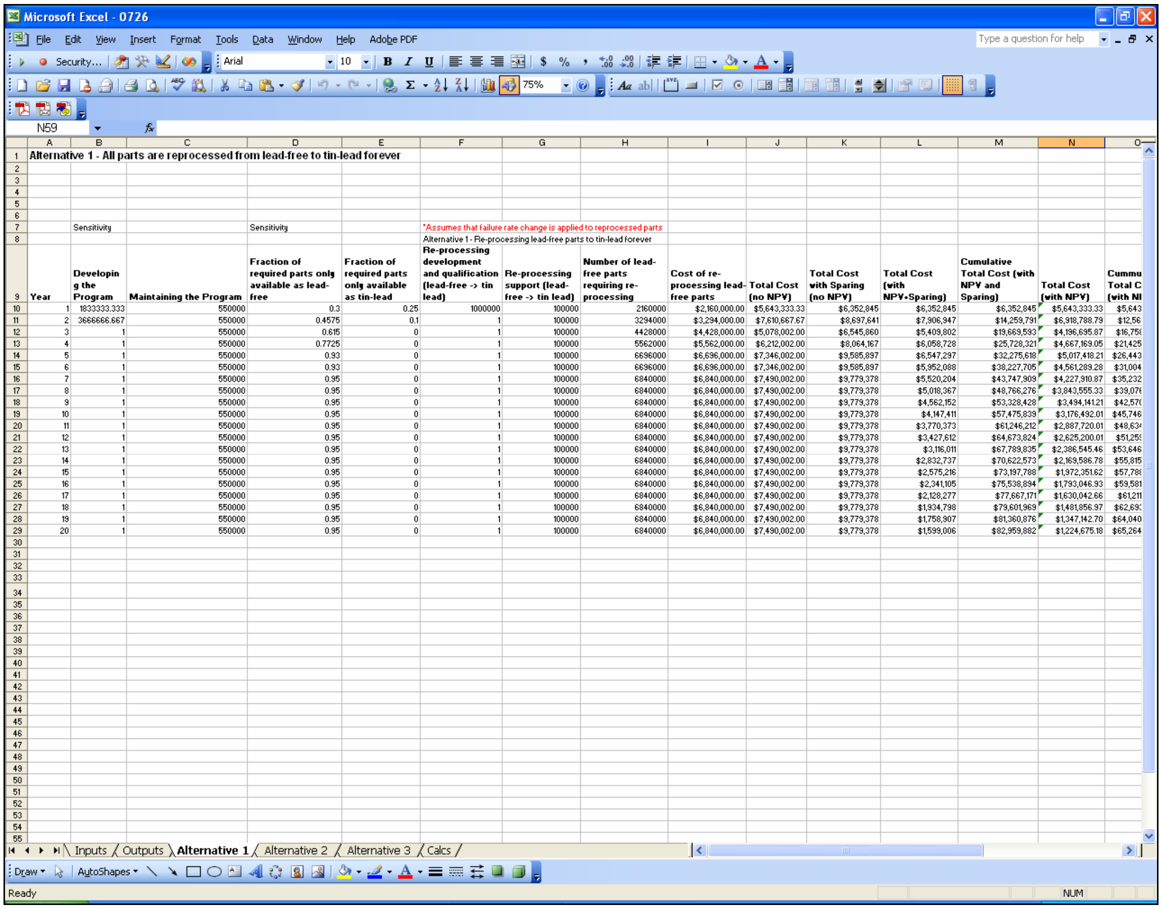
| | Alternative 1 (reprocess lead-free to tin-lead) | | Alternative 2 (mixed assembly) | | Alternative 3 (reprocess tin-lead to lead-free) | |
|---|---|---|---|---|---|---|
| **Year** | **Annual Cost** | **Cumulative Cost** | **Annual Cost** | **Cumulative Cost** | **Annual Cost** | **Cumulative Cost** |
| **1** | $6,352,844.59 | $6,352,844.59 | $7,997,877.62 | $7,997,877.62 | $9,461,506.33 | $9,461,506.33 |
| **2** | $7,906,946.64 | $14,259,791.24 | $9,261,138.63 | $17,259,016.24 | $7,285,230.47 | $16,746,736.81 |
| **3** | $5,409,801.68 | $19,669,592.92 | $5,581,719.79 | $22,840,736.03 | $2,390,933.54 | $19,137,670.35 |
| **4** | $6,058,728.02 | $25,728,320.94 | $5,074,290.72 | $27,915,026.75 | $2,173,575.95 | $21,311,246.30 |
| **5** | $6,547,296.66 | $32,275,617.60 | $4,612,991.56 | $32,528,018.31 | $1,975,978.13 | $23,287,224.43 |
| **6** | $5,952,087.88 | $38,227,705.48 | $4,193,628.69 | $36,721,647.00 | $1,796,343.76 | $25,083,568.19 |
| **7** | $5,520,203.69 | $43,747,909.17 | $4,117,883.01 | $40,839,530.01 | $1,938,533.07 | $27,022,101.26 |
| **8** | $5,018,366.99 | $48,766,276.16 | $6,268,267.95 | $47,107,797.97 | $4,287,040.73 | $31,309,142.00 |
| **9** | $4,562,151.81 | $53,328,427.98 | $7,993,641.72 | $55,101,439.69 | $6,192,526.07 | $37,501,668.07 |
| **10** | $4,147,410.74 | $57,475,838.71 | $9,353,507.30 | $64,454,946.99 | $7,716,129.44 | $45,217,797.50 |
| **11** | $3,770,373.40 | $61,246,212.11 | $10,400,061.44 | $74,855,008.43 | $8,911,536.11 | $54,129,333.61 |
| **12** | $3,427,612.18 | $64,673,824.29 | $11,179,031.29 | $86,034,039.72 | $9,825,826.45 | $63,955,160.06 |
| **13** | $3,116,011.07 | $67,789,835.36 | $11,730,419.35 | $97,764,459.07 | $10,500,233.12 | $74,455,393.18 |
| **14** | $2,832,737.34 | $70,622,572.70 | $12,089,166.34 | $109,853,625.40 | $10,970,815.22 | $85,426,208.40 |
| **15** | $2,575,215.76 | $73,197,788.46 | $12,285,740.99 | $122,139,366.39 | $11,269,058.15 | $96,695,266.55 |
| **16** | $2,341,105.24 | $75,538,893.70 | $12,346,664.32 | $134,486,030.71 | $11,422,407.20 | $108,117,673.76 |
| **17** | $2,128,277.49 | $77,667,171.19 | $12,294,975.64 | $146,781,006.36 | $11,454,741.90 | $119,572,415.66 |
| **18** | $1,934,797.72 | $79,601,968.91 | $12,150,646.36 | $158,931,652.71 | $11,386,797.50 | $130,959,213.15 |
| **19** | $1,758,907.02 | $81,360,875.93 | $11,930,947.39 | $170,862,600.10 | $11,236,539.33 | $142,195,752.49 |
| **20** | $1,599,006.38 | $82,959,882.31 | $11,650,775.12 | $182,513,375.22 | $11,019,495.07 | $153,215,247.56 |

| | |
|---|---|
| **Alternative 1** | Reprocess lead-free parts to tin-lead forever |
| **Alternative 2** | Mixed assembly |
| **Alternative 3** | Reprocess tin-lead parts to lead-free forever |

**Figure 2 – *Outputs* sheet.**

### *Alternative 1 – All Tin-Lead Solution*

Alternative 1 is the option where tin-lead parts are used if possible and when not possible lead-free parts are reprocessed to tin-lead parts. A tin-lead assembly process is used. Costs involved in plan development, reprocessing, sparing due to reprocessing as well as annual costs and cumulative costs are displayed for the user to see. All costs are in year 1 dollars.



Alternative 1 - All parts are reprocessed from lead-free to tin-lead forever

Sensitivity

Sensitivity

*Assumes that failure rate change is applied to reprocessed parts

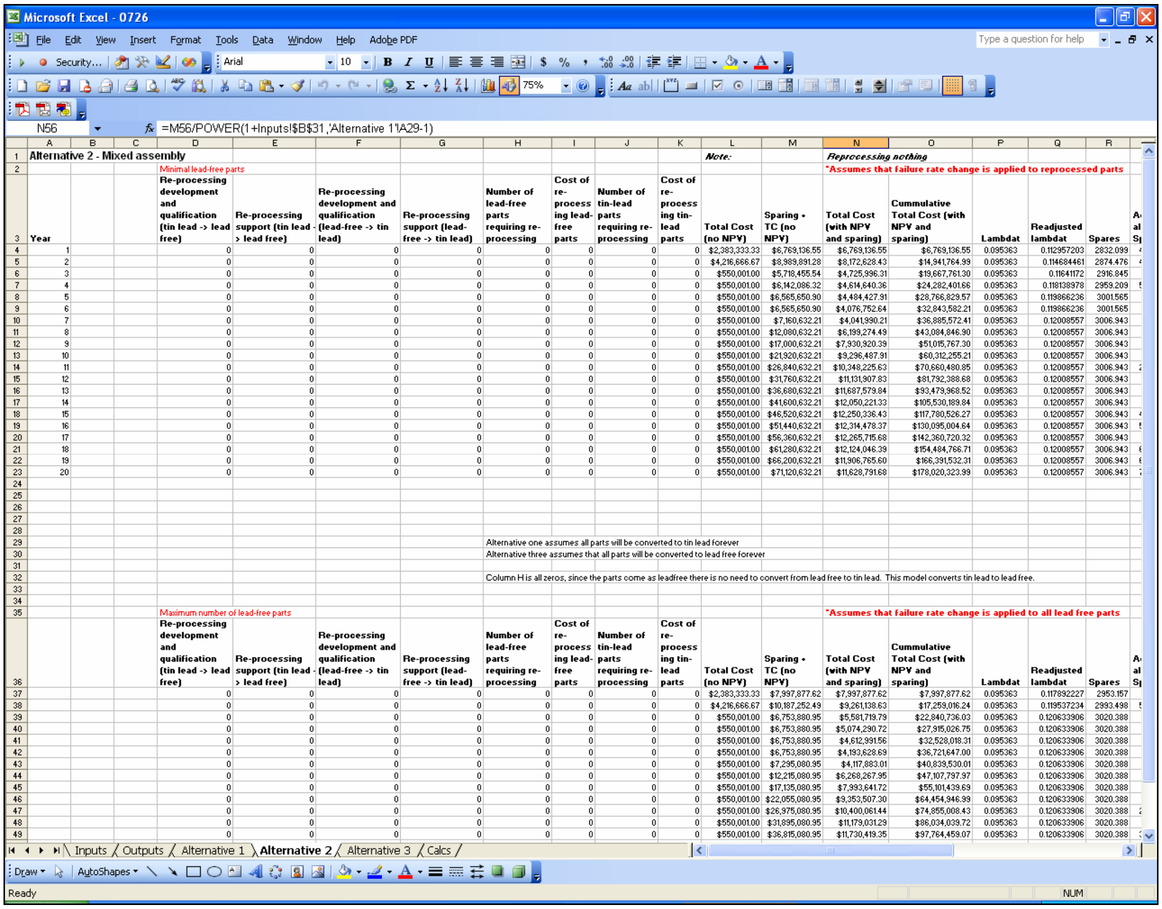
Alternative 1 - Re-processing lead-free parts to tin-lead forever

| Year | Developing the Program | Maintaining the Program | Fraction of required parts only available as lead-free | Fraction of required parts only available as tin-lead | Re-processing development and qualification (lead-free -> tin lead) | Re-processing support (lead-free -> tin lead) | Number of lead-free parts requiring re-processing | Cost of re-processing lead-free parts | Total Cost (no NPV) | Total Cost with Sparing (no NPV) | Total Cost (with NPV+Sparing) | Cumulative Total Cost (with NPV and Sparing) | Total Cost (with NPV) | Cummu Total C (with NI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1833333.333 | 550000 | 0.3 | 0.25 | 1000000 | 100000 | 2160000 | $2,160,000.00 | $5,643,333.33 | $6,352,845 | $6,352,845 | $6,352,845 | $5,643,333.33 | $5,643 |
| 2 | 3666666.667 | 550000 | 0.4575 | 0.1 | 1 | 100000 | 3294000 | $3,294,000.00 | $7,610,667.67 | $8,697,641 | $7,906,947 | $14,259,791 | $6,918,788.79 | $12,56 |
| 3 | 1 | 550000 | 0.615 | 0 | 1 | 100000 | 4428000 | $4,428,000.00 | $5,078,002.00 | $6,545,860 | $5,409,802 | $19,669,593 | $4,196,695.87 | $16,75 |
| 4 | 1 | 550000 | 0.7725 | 0 | 1 | 100000 | 5562000 | $5,562,000.00 | $6,212,002.00 | $8,064,167 | $6,058,728 | $25,728,321 | $4,667,169.05 | $21,425 |
| 5 | 1 | 550000 | 0.93 | 0 | 1 | 100000 | 6696000 | $6,696,000.00 | $7,346,002.00 | $9,585,897 | $6,547,297 | $32,275,618 | $5,017,418.21 | $26,443 |
| 6 | 1 | 550000 | 0.93 | 0 | 1 | 100000 | 6696000 | $6,696,000.00 | $7,346,002.00 | $9,585,897 | $5,952,088 | $38,227,705 | $4,561,289.28 | $31,004 |
| 7 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $5,520,204 | $43,747,909 | $4,227,910.87 | $35,232 |
| 8 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $5,018,367 | $48,766,276 | $3,843,555.33 | $39,07 |
| 9 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $4,562,152 | $53,328,428 | $3,494,141.21 | $42,57 |
| 10 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $4,147,411 | $57,475,839 | $3,176,492.01 | $45,746 |
| 11 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $3,770,373 | $61,246,212 | $2,887,720.01 | $48,63 |
| 12 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $3,427,612 | $64,673,824 | $2,625,200.01 | $51,25 |
| 13 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $3,116,011 | $67,789,835 | $2,386,545.46 | $53,646 |
| 14 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $2,832,737 | $70,622,573 | $2,169,586.78 | $55,815 |
| 15 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $2,575,216 | $73,197,788 | $1,972,351.62 | $57,78 |
| 16 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $2,341,105 | $75,538,894 | $1,793,046.93 | $59,581 |
| 17 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $2,128,277 | $77,667,171 | $1,630,042.66 | $61,211 |
| 18 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $1,934,798 | $79,601,969 | $1,481,856.97 | $62,69 |
| 19 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $1,758,907 | $81,360,876 | $1,347,142.70 | $64,040 |
| 20 | 1 | 550000 | 0.95 | 0 | 1 | 100000 | 6840000 | $6,840,000.00 | $7,490,002.00 | $9,779,378 | $1,599,006 | $82,959,882 | $1,224,675.18 | $65,264 |

**Figure 3 – *Alternative 1* sheet.**

### *Alternative 2 – Mixed Tin-Lead/Lead-Free Assembly*

Alternative 2 is the option where a mixed assembly is performed. In this case tin-lead parts are used if possible and when not possible lead-free parts are used. This option also takes into consideration the extra cost incurred due to tin whisker failures. All costs are in year 1 dollars. The top data set applies the failure rate change to the parts that are only available as lead-free. However there is a certain percentage of parts that come in both the tin-lead and lead-free forms. The bottom data set applies the failure rate change to all parts that can possibly be lead-free; this includes the parts that are available only as lead-free as well as parts that are available as lead-free and tin-lead.



=M56/POWER(1+Inputs!$B$31,'Alternative 1'!A29-1)

Alternative 2 - Mixed assembly

Minimal lead-free parts

Note:

Reprocessing nothing

*Assumes that failure rate change is applied to reprocessed parts

| Year | | | Re-processing development and qualification (tin lead -> lead free) | Re-processing support (tin lead -> lead free) | Re-processing development and qualification (lead-free -> tin lead) | Re-processing support (lead-free -> tin lead) | Number of lead-free parts requiring re-processing | Cost of re-processing lead-free parts | Number of tin-lead parts requiring re-processing | Cost of re-processing tin-lead parts | Total Cost (no NPV) | Sparing + TC (no NPV) | Total Cost (with NPV and sparing) | Cummulative Total Cost (with NPV and sparing) | Lambdat | Readjusted lambdat | Spares |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $2,383,333.33 | $6,769,136.55 | $6,769,136.55 | $6,769,136.55 | 0.095363 | 0.112957203 | 2832.099 |
| 2 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $4,216,666.67 | $8,989,891.28 | $8,172,628.43 | $14,941,764.99 | 0.095363 | 0.114684461 | 2874.476 |
| 3 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $5,718,455.54 | $4,725,996.31 | $19,667,761.30 | 0.095363 | 0.11641172 | 2916.845 |
| 4 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,142,086.32 | $4,614,640.36 | $24,282,401.66 | 0.095363 | 0.118138978 | 2959.209 |
| 5 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,565,650.90 | $4,484,427.91 | $28,766,829.57 | 0.095363 | 0.119866236 | 3001.565 |
| 6 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,565,650.90 | $4,076,752.64 | $32,843,582.21 | 0.095363 | 0.119866236 | 3001.565 |
| 7 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $7,160,632.21 | $4,041,990.21 | $36,885,572.41 | 0.095363 | 0.12008557 | 3006.943 |
| 8 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $12,080,632.21 | $6,199,274.49 | $43,084,846.90 | 0.095363 | 0.12008557 | 3006.943 |
| 9 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $17,000,632.21 | $7,930,920.39 | $51,015,767.30 | 0.095363 | 0.12008557 | 3006.943 |
| 10 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $21,920,632.21 | $9,296,487.91 | $60,312,255.21 | 0.095363 | 0.12008557 | 3006.943 |
| 11 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $26,840,632.21 | $10,348,225.63 | $70,660,480.85 | 0.095363 | 0.12008557 | 3006.943 |
| 12 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $31,760,632.21 | $11,131,907.83 | $81,792,388.68 | 0.095363 | 0.12008557 | 3006.943 |
| 13 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $36,680,632.21 | $11,687,579.84 | $93,479,968.52 | 0.095363 | 0.12008557 | 3006.943 |
| 14 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $41,600,632.21 | $12,050,221.33 | $105,530,189.84 | 0.095363 | 0.12008557 | 3006.943 |
| 15 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $46,520,632.21 | $12,250,336.43 | $117,780,526.27 | 0.095363 | 0.12008557 | 3006.943 |
| 16 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $51,440,632.21 | $12,314,478.37 | $130,095,004.64 | 0.095363 | 0.12008557 | 3006.943 |
| 17 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $56,360,632.21 | $12,265,715.68 | $142,360,720.32 | 0.095363 | 0.12008557 | 3006.943 |
| 18 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $61,280,632.21 | $12,124,046.39 | $154,484,766.71 | 0.095363 | 0.12008557 | 3006.943 |
| 19 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $66,200,632.21 | $11,906,765.60 | $166,391,532.31 | 0.095363 | 0.12008557 | 3006.943 |
| 20 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $71,120,632.21 | $11,628,791.68 | $178,020,323.99 | 0.095363 | 0.12008557 | 3006.943 |

Alternative one assumes all parts will be converted to tin lead forever

Alternative three assumes that all parts will be converted to lead free forever

Column H is all zeros, since the parts come as leadfree there is no need to convert from lead free to tin lead. This model converts tin lead to lead free.

Maximum number of lead-free parts

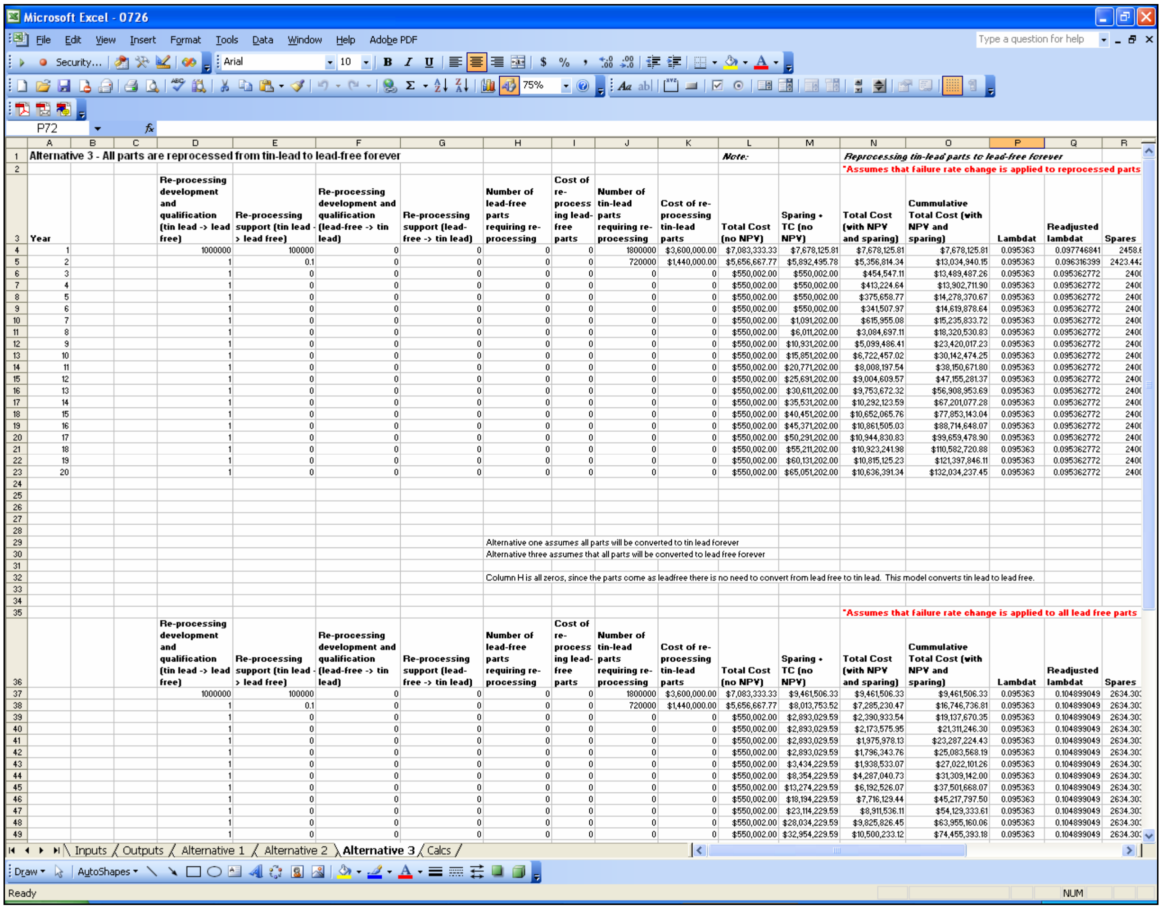
*Assumes that failure rate change is applied to all lead free parts

| | | | Re-processing development and qualification (tin lead -> lead free) | Re-processing support (tin lead -> lead free) | Re-processing development and qualification (lead-free -> tin lead) | Re-processing support (lead-free -> tin lead) | Number of lead-free parts requiring re-processing | Cost of re-processing lead-free parts | Number of tin-lead parts requiring re-processing | Cost of re-processing tin-lead parts | Total Cost (no NPV) | Sparing + TC (no NPV) | Total Cost (with NPV and sparing) | Cummulative Total Cost (with NPV and sparing) | Lambdat | Readjusted lambdat | Spares |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $2,383,333.33 | $7,997,877.62 | $7,997,877.62 | $7,997,877.62 | 0.095363 | 0.117892227 | 2953.157 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $4,216,666.67 | $10,187,252.49 | $9,261,138.63 | $17,259,016.24 | 0.095363 | 0.119537234 | 2993.498 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,753,880.95 | $5,581,719.79 | $22,840,736.03 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,753,880.95 | $5,074,290.72 | $27,915,026.75 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,753,880.95 | $4,612,991.56 | $32,528,018.31 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $6,753,880.95 | $4,193,628.69 | $36,721,647.00 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $7,295,080.95 | $4,117,883.01 | $40,839,530.01 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $12,215,080.95 | $6,268,267.95 | $47,107,797.97 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $17,135,080.95 | $7,993,641.72 | $55,101,439.69 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $22,055,080.95 | $9,353,507.30 | $64,454,946.99 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $26,975,080.95 | $10,400,061.44 | $74,855,008.43 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $31,895,080.95 | $11,179,031.29 | $86,034,039.72 | 0.095363 | 0.120633906 | 3020.388 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,001.00 | $36,815,080.95 | $11,730,419.35 | $97,764,459.07 | 0.095363 | 0.120633906 | 3020.388 |

**Figure 4 - *Alternative 2* sheet.**

### *Alternative 3 – All Lead-Free Solution*

Alternative 3 is the option where lead-free parts are used if available, and when not available tin-lead parts are reprocessed to lead-free parts. Costs involved in plan development, reprocessing, sparing due to reprocessing and sparing due to tin whisker failures as well as annual costs and cumulative costs are displayed for the user to see. All costs are in year 1 dollars. The worksheet has two sets of data. The data set at the top assumes that there is a change in failure rate for only reprocessed parts whereas the data set at the bottom assumes that there is a change in failure rate for all lead-free parts.



Alternative 3 - All parts are reprocessed from tin-lead to lead-free forever

*Note:* *Reprocessing tin-lead parts to lead-free forever*

*Assumes that failure rate change is applied to reprocessed parts

| | Year | | | Re-processing development and qualification (tin lead -> lead free) | Re-processing support (tin lead -> lead free) | Re-processing development and qualification (lead-free -> tin lead) | Re-processing support (lead-free -> tin lead) | Number of lead-free parts requiring re-processing | Cost of re-processing lead-free parts | Number of tin-lead parts requiring re-processing | Cost of re-processing tin-lead parts | Total Cost (no NPV) | Sparing + TC (no NPV) | Total Cost (with NPV and sparing) | Cummulative Total Cost (with NPV and sparing) | Lambdat | Readjusted lambdat | Spares |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | | | 1000000 | 100000 | 0 | 0 | 0 | 0 | 1800000 | $3,600,000.00 | $7,083,333.33 | $7,678,125.81 | $7,678,125.81 | $7,678,125.81 | 0.095363 | 0.097746841 | 2458. |
| 5 | 2 | | | 1 | 0.1 | 0 | 0 | 0 | 0 | 720000 | $1,440,000.00 | $5,656,667.77 | $5,892,495.78 | $5,356,814.34 | $13,034,940.15 | 0.095363 | 0.096316399 | 2423.44 |
| 6 | 3 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $550,002.00 | $454,547.11 | $13,489,487.26 | 0.095363 | 0.095362772 | 240 |
| 7 | 4 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $550,002.00 | $413,224.64 | $13,902,711.90 | 0.095363 | 0.095362772 | 240 |
| 8 | 5 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $550,002.00 | $375,658.77 | $14,278,370.67 | 0.095363 | 0.095362772 | 240 |
| 9 | 6 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $550,002.00 | $341,507.97 | $14,619,878.64 | 0.095363 | 0.095362772 | 240 |
| 10 | 7 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $1,091,202.00 | $615,955.08 | $15,235,833.72 | 0.095363 | 0.095362772 | 240 |
| 11 | 8 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $6,011,202.00 | $3,084,697.11 | $18,320,530.83 | 0.095363 | 0.095362772 | 240 |
| 12 | 9 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $10,931,202.00 | $5,099,486.41 | $23,420,017.23 | 0.095363 | 0.095362772 | 240 |
| 13 | 10 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $15,851,202.00 | $6,722,457.02 | $30,142,474.25 | 0.095363 | 0.095362772 | 240 |
| 14 | 11 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $20,771,202.00 | $8,008,197.54 | $38,150,671.80 | 0.095363 | 0.095362772 | 240 |
| 15 | 12 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $25,691,202.00 | $9,004,609.57 | $47,155,281.37 | 0.095363 | 0.095362772 | 240 |
| 16 | 13 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $30,611,202.00 | $9,753,672.32 | $56,908,953.69 | 0.095363 | 0.095362772 | 240 |
| 17 | 14 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $35,531,202.00 | $10,292,123.59 | $67,201,077.28 | 0.095363 | 0.095362772 | 240 |
| 18 | 15 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $40,451,202.00 | $10,652,065.76 | $77,853,143.04 | 0.095363 | 0.095362772 | 240 |
| 19 | 16 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $45,371,202.00 | $10,861,505.03 | $88,714,648.07 | 0.095363 | 0.095362772 | 240 |
| 20 | 17 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $50,291,202.00 | $10,944,830.83 | $99,659,478.90 | 0.095363 | 0.095362772 | 240 |
| 21 | 18 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $55,211,202.00 | $10,923,241.98 | $110,582,720.88 | 0.095363 | 0.095362772 | 240 |
| 22 | 19 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $60,131,202.00 | $10,815,125.23 | $121,397,846.11 | 0.095363 | 0.095362772 | 240 |
| 23 | 20 | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $65,051,202.00 | $10,636,391.34 | $132,034,237.45 | 0.095363 | 0.095362772 | 240 |

Alternative one assumes all parts will be converted to tin lead forever

Alternative three assumes that all parts will be converted to lead free forever

Column H is all zeros, since the parts come as leadfree there is no need to convert from lead free to tin lead.  This model converts tin lead to lead free.

*Assumes that failure rate change is applied to all lead free parts

| | | | | Re-processing development and qualification (tin lead -> lead free) | Re-processing support (tin lead -> lead free) | Re-processing development and qualification (lead-free -> tin lead) | Re-processing support (lead-free -> tin lead) | Number of lead-free parts requiring re-processing | Cost of re-processing lead-free parts | Number of tin-lead parts requiring re-processing | Cost of re-processing tin-lead parts | Total Cost (no NPV) | Sparing + TC (no NPV) | Total Cost (with NPV and sparing) | Cummulative Total Cost (with NPV and sparing) | Lambdat | Readjusted lambdat | Spares |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 37 | | | | 1000000 | 100000 | 0 | 0 | 0 | 0 | 1800000 | $3,600,000.00 | $7,083,333.33 | $9,461,506.33 | $9,461,506.33 | $9,461,506.33 | 0.095363 | 0.104899049 | 2634.30 |
| 38 | | | | 1 | 0.1 | 0 | 0 | 0 | 0 | 720000 | $1,440,000.00 | $5,656,667.77 | $8,013,753.52 | $7,285,230.47 | $16,746,736.81 | 0.095363 | 0.104899049 | 2634.30 |
| 39 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $2,893,029.59 | $2,390,933.54 | $19,137,670.35 | 0.095363 | 0.104899049 | 2634.30 |
| 40 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $2,893,029.59 | $2,173,575.95 | $21,311,246.30 | 0.095363 | 0.104899049 | 2634.30 |
| 41 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $2,893,029.59 | $1,975,978.13 | $23,287,224.43 | 0.095363 | 0.104899049 | 2634.30 |
| 42 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $2,893,029.59 | $1,796,343.76 | $25,083,568.19 | 0.095363 | 0.104899049 | 2634.30 |
| 43 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $3,434,229.59 | $1,938,533.07 | $27,022,101.26 | 0.095363 | 0.104899049 | 2634.30 |
| 44 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $8,354,229.59 | $4,287,040.73 | $31,309,142.00 | 0.095363 | 0.104899049 | 2634.30 |
| 45 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $13,274,229.59 | $6,192,526.07 | $37,501,668.07 | 0.095363 | 0.104899049 | 2634.30 |
| 46 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $18,194,229.59 | $7,716,129.44 | $45,217,797.50 | 0.095363 | 0.104899049 | 2634.30 |
| 47 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $23,114,229.59 | $8,911,536.11 | $54,129,333.61 | 0.095363 | 0.104899049 | 2634.30 |
| 48 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $28,034,229.59 | $9,825,826.45 | $63,955,160.06 | 0.095363 | 0.104899049 | 2634.30 |
| 49 | | | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $550,002.00 | $32,954,229.59 | $10,500,233.12 | $74,455,393.18 | 0.095363 | 0.104899049 | 2634.30 |

**Figure 5 – *Alternative 3* sheet.**

## *Calcs Sheet*

This worksheet contains intermediary calculations such as number of parts, z value for the confidence interval chosen, spares, etc.  These cells are used solely for cost calculations for each of the alternatives.  The user must not change or interact with these cells.

## Tutorial

### *Step 1*

Open the spreadsheet (you must select “Enable Macros” in the Security Warning if asked).

### *Step 2*

Go to the *Inputs* tab. This is the worksheet where all the inputs are entered. Click on the *Outputs* tab. This worksheet will have the results displayed in tabular and graphical form. The annual cost and cumulative costs incurred due to the specific set of inputs are seen in this worksheet.

### *Step 3*

Click on the *Inputs* tab again and change the number of boards from 24 to 1000. Click on the pink *Run Cost Model* button. A cost calculation will be performed using the modified inputs by the tool and you will automatically be relocated to the *Outputs* sheet. This change in input can be visualized in the graph and table values in *Outputs*. The *Alternative 1*, *Alternative 2* and *Alternative 3* sheets can be chosen to view the changes in detail.

### *Step 4*

Continue making changes as required in the *Inputs* sheet. The *Run Cost Model* button must be clicked in order for input changes to be included in the calculations.

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