Cost Model for Assessing the Transition to Lead-Free Electronics

Peter Sandborn and Rifat Jafreen
CALCE Electronic Products and System Center
Department of Mechanical Engineering
University of Maryland

Abstract

This paper describes a cost model developed to assess the cost ramifications of the transition from tin-lead to lead-free electronic parts. All tin-lead, all lead-free and mixed assembly approaches are considered. The model makes basic assumptions of a fixed generic set of applications, incorporates a cost of plan development, and includes the costs of reprocessing tin lead to lead free and vice versa. In addition, the model takes into consideration the cost of money and assumptions about tin-lead and lead-free part available over time. Reliability impacts of the lead-free transition are cost modeled as changes to the number of required spares.

Introduction

Recently there has been a lot of attention focused on developing lead-free products, [1]. Whether exempt or non-exempt from Regulation of Hazardous Substances (RoHS), organizations are being forced to transition their products to lead-free as tin-lead solder finish electronic parts become unavailable. There are significant cost and risk implications associated with making the transition to lead-free. The path taken by an organization to deal with lead-free parts and the unavailability of conventional tin-lead parts will have long-term financial ramifications for the organization, and the degree to which industry coordinates the requirements passed to their supply chains will financially impact everyone.

This paper describes a cost model developed in collaboration with the Lead-free Electronics in Aerospace Project (LEAP) Working Group to assess the ramifications of the lead-free transition, [2]. Organizations will be presented with many options on how to adapt to the new lead-free situation. In this paper, three basic scenarios are considered: 1) an all lead-free assembly process using lead-free parts as soon as they are available (tin-lead parts are reprocessed into lead-free parts when required); 2) an all tin-lead process (re-process lead-free parts when necessary into tin-lead parts and use them in conventional assembly processes); and 3) a qualified mixed assembly of tin-lead and lead-free parts assembled with tin-lead solder. In order to aide organizations in choosing the approach to take, the model predicts the cumulative costs for each of these options over a 10 year period by taking into account all costs involved in sustaining each of the options.

Modeling Approach

The general approach to managing the transition to lead-free parts is to assimilate the costs involved for each of the options cumulatively for a specified number of years. In order to determine these costs, several effects must be modeled. These effects include: variation as a function of time in the number of parts available as tin-lead and lead-free, and reprocessing costs per board, per part and/or per I/O (reprocessing from tin-lead to lead-free and vice versa). There will be fixed costs such as process and part qualification, the tooling required for reprocessing, as well as the NRE costs to implement the program. If parts are reprocessed or mixtures of lead-free and tin-lead parts are used, the reliability of the part 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.

The total cost associated with a particular approach to managing lead-free parts in year i is given by,

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

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 remainder of this section summarizes the specific costs included within the model in (1). The cost modeling approach developed in this paper is a "relative" cost model. It is relative in the sense that all costs that are approximately independent of whether lead-free or tin-lead parts are used, are omitted from the model, i.e., the model is based on changes in key quantities rather than the quantities themselves. Therefore, the absolute cost numbers generated by this model do not have as much accuracy as the cost differences between two cases (e.g., that differ by lead-free content). The reason for constructing the cost model in this way is that the cost differences can be much more accurately modeled than absolute costs.

Reprocessing Costs

Reprocessing cost describes the cost involved in changing a tin-lead part to lead-free and vice versa. The cost of reprocessing is generally given by,

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

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.

Note, the non-recurring cost of qualifying a reprocessing process is included in the NRE cost of plan development and implementation. Equation (1) also requires that the number of parts reprocessed be determined,

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

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.

Figure 1 shows the assumed availability of parts as only lead-free or only tin-lead over a period of 10 years. Note, Figure 1 assumes that there is an overlap of parts that are available as both tin-lead and lead-free. Figure 1 also shows a modification to the availability profile if legacy tin-lead parts are available (e.g., from a lifetime buy). The modification in year 1 is given by,

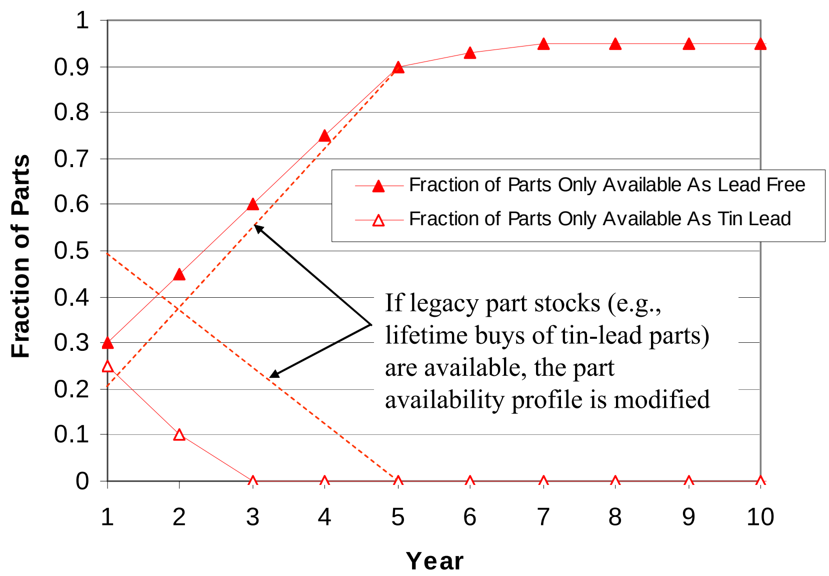

Figure 1- Fraction of parts available only as tin-lead or lead-free.

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

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 year that the legacy part inventory is depleted. Note, if the legacy parts are disposed of, the money invested in those legacy parts must also be added to the cost of supporting the product.

Impacts on Sparing

Reprocessing tin-lead parts to lead-free and vice versa, or fabricating mixed tin-lead/lead-free systems has a possible effect on the reliability of the system. In our approach, the cost of failure rate changes is determined by changes in the number of spare boards that need to be manufactured each year to maintain the system.

For a board, the number of spares required is given by,[1]

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

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, [4].

The calculation of the change in the number of required spares begins by assuming an original number of spares needed to support the conventional tin-lead version of the system, k_{orig}. Using k_{orig} in (5) with a

[1] When the number of spares (k) is large, the Poisson distribution can be approximated by the normal distribution and k can be approximated in the closed form given in (5), [3].

value of z computed from the desired confidence level, allows the calculation of the original $n\lambda t$. The value of $n\lambda t$ is then adjusted for a specified or computed board-level failure rate change and (5) is used to compute the new number of spares, k_{new}. 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 (6),

$$C_{spares} = \Delta k\left(N_{rp}C_{rp} + C_{board}\right) \tag{6}$$

where C_{board} is the cost of procuring a conventional version of the spare board (including part costs, assembly, testing, etc.).

The change in the quantity $n\lambda t$ to reflect a change in the failure rate is determined using the following process. Assuming a constant failure rate,

$$\left(e^{-\lambda t_{new}}\right)^{N_b} = \left(e^{-\lambda t_0}\right)^{N_b - N_{rp}}\left(e^{-\lambda t_0(1-M)}\right)^{N_{rp}} \tag{7}$$

where,

λt_0 = original λt of a <u>part</u> (~original λt of the <u>system</u> divided by N_b)
λt_{new} = new effective λt 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.

Equation (7) can be solved for λt_{new},

$$\lambda t_{new} = \lambda t_0\left(1 - \frac{MN_{rp}}{N_b}\right) \tag{8}$$

The modified λt that needs to be used in (5) is $N_b\lambda t_{new}$. Notice that the actual values of the failure rates are never needed (only the change in the failure rates, M). The development above is valid for a constant failure rate assumption (as expressed in (7)) and would also be valid for Weibull failure distributions.

Plan Implementation and Maintenance

There will be several overhead costs involved in managing the transition to lead-free parts. A plan, where a "plan" could be a unique combination of materials and/or qualifications requirements, will have one-time implementation and annual maintenance costs. The basic implementation costs assumed for this model is given by (9),

$$C_{plan} = \frac{C_{plan1}}{z_1} + \sum_{k=2}^{n}\frac{(1-c)C_{plan}}{1} + C_{rp_{NRE}} \tag{9}$$

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)
f_m = fraction of a plans development and implementation cost charged per year to maintain the plan
C_{rpNRE} = NRE cost associated with reprocessing.

Note, the implementation of subsequent plans is assumed to happen in 1 year in (9). The basic plan maintenance costs assumed for this model are given by (10),

$$C_{plan\ maint} = f_m C_{plan} + \sum_{k=2}^{n} f_m (1 - c) C_{plan} \tag{10}$$

Note, various portions of (9) and (10) may appear in various years within the calculation.

Results

The model described in the last section has been used to assess the three basic scenarios: 1) an all lead-free assembly process using lead-free parts as soon as they are available (tin-lead parts are reprocessed into lead-free parts when required); 2) an all tin-lead process (re-process lead-free parts when necessary into tin-lead parts and use them in conventional assembly processes); and 3) a qualified mixed assembly of tin-lead and lead-free parts assembled with tin-lead solder. The assessment is performed for various assumptions about the number of plans supported by the system manufacturer and the effective rate at which lead-free parts displace tin-lead parts.

The baseline values of the input parameters assumed in this study are given in Table 1.

Table 1: Input Parameters

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})	\$5,500,000
Plan Maintenance (fraction of C_{plan1}) (f_m)	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

Figure 2 shows the annual and cumulative cost associated the three approaches considered in this analysis. The annual costs are initially larger (due to one-time plan development and implementation costs and reprocessing NRE costs). Annual costs in later years have a negative slope due to the non-zero cost of money assumed, i.e., future dollars cost less than today's dollars (no inflation is assumed). After 10 years, the difference between the all lead-free solution and the mixed assembly solution is approximately \$18 million. The cost of building all tin-lead assemblies accelerates in out years because the number of parts that must be reprocessed to support this solution increases while the cumulative cost of the all lead-free solution slows down as all parts become available in lead-free format.

In the results that follow, we will focus on the cumulative costs over a 10 year period. In Figures 3, 4 and 6, the right side of the figure is the same as the right side in Figure 2 (e.g., the baseline case is provided for comparison purposes).

Figure 3 shows the cumulative costs for two different quantities of boards produced per year. The difference between the all lead-free solution and the other solutions approximately scales with the quantity of boards produced.

Figure 4 shows the impact of the number of plans considered. On the left side of Figure 4, the manufacturer is supporting 10 different plans with an assumed 65% commonality (c) between the plans. The figure shows that there is a cumulative cost difference of approximately \$31 million after 10 years between supporting one plan and supporting 10 plans.

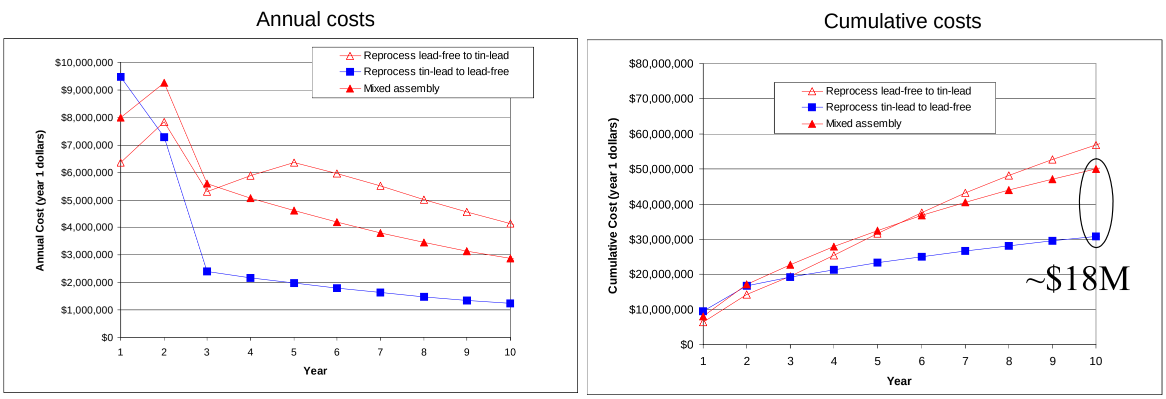

Figure 2 - Annual (left) and cumulative (right) costs for the baseline data in Table 1 for one plan.

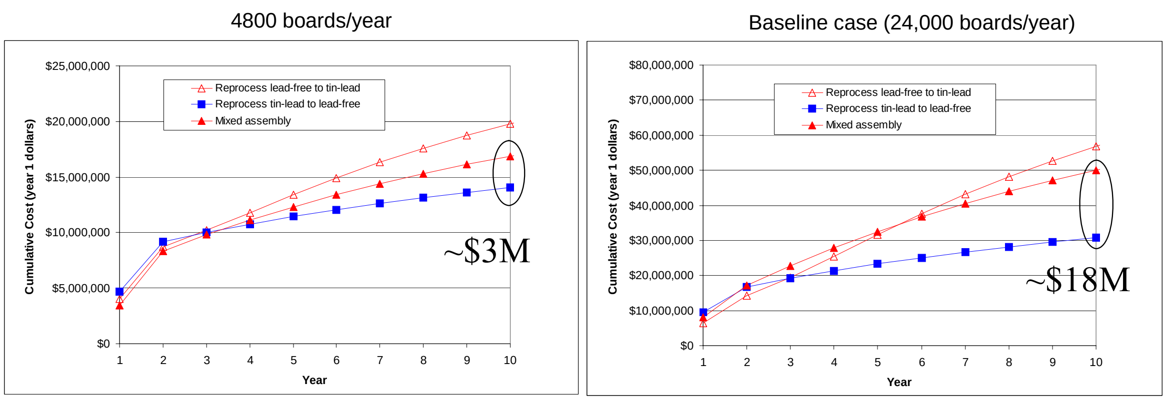

Figure 3 - Effect of board production quantity on cumulative costs. Left = 4800 boards/year, Right = 24,000 boards/year.

Taking the result in Figure 4 a step further, consider the effect of the cost per plan on the 10 year cumulative cost for 40% and 90% plan commonality for two different extremes in estimated plan NRE costs (Figure 5). The difference between one plan and ten plans ranges from \$8 million to \$161 million depending on the commonality and NRE costs.

When electronic parts become obsolete (i.e., they are no longer procurable from the original supplier), lifetime or bridge buys of parts are often made, [5]. A lifetime buy means purchasing enough parts to last until the end of support life for the system (a bridge buy means buying enough parts to last until a scheduled design refresh that will result in the part being design out of the system). Therefore, some

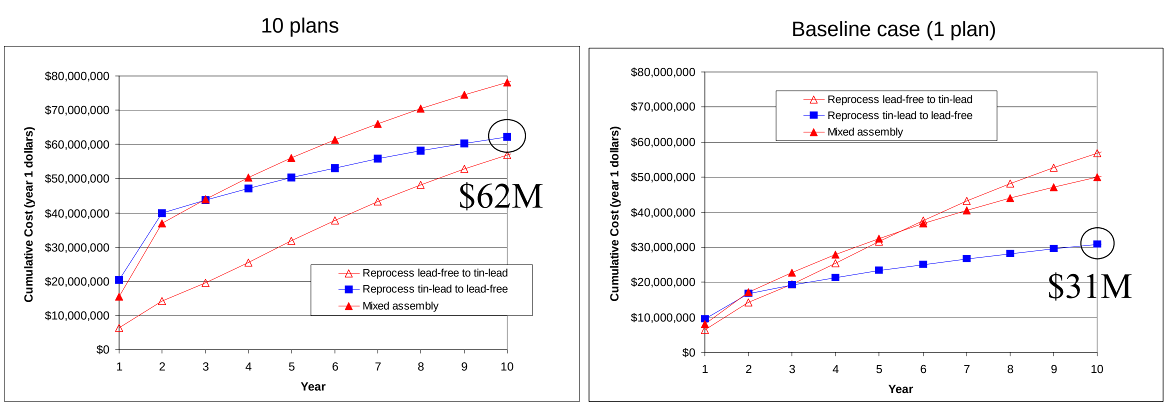

Figure 4 - Effect of the number of different plans supported by the supplier. Left = 10 plans, Right = 1 plan. 65% commonality between plans assumed.

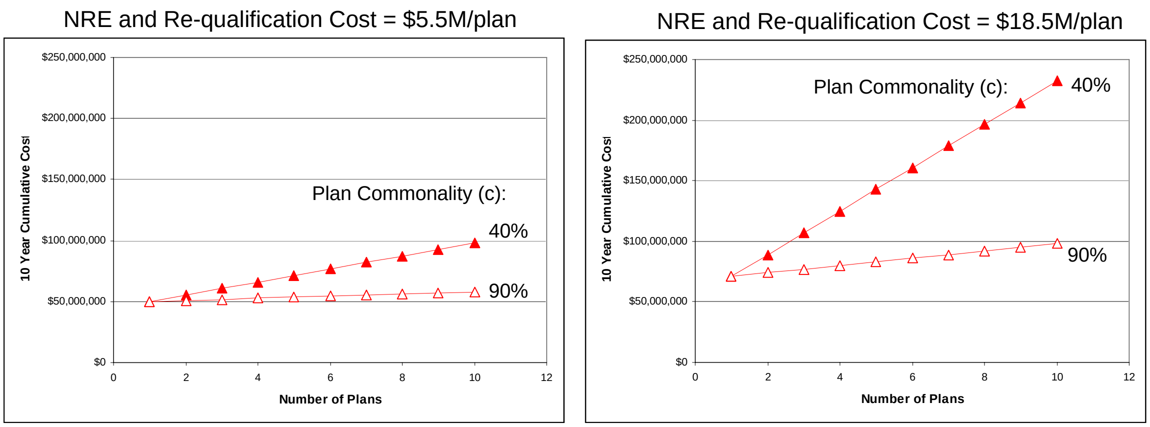

Figure 5 - The 10 year cumulative cost of different quantities of plans supported by the supplier as a function of the plan commonality. NRE and qualification cost: Left = $5.5 million/plan, Right = $18.5 million/plan.

fraction of the parts in a system will have existing lifetime/bridge buys of tin-lead parts. Depending on when those lifetime/bridge buys run out and how you choose to use existing inventories of tin-lead parts, the relative costs of the lead-free management options changes. The results in Figure 6 assume that 30% of the parts have a 5 year lifetime buy and the lifetime buy parts are going to be used (as opposed to disposed of) – this part availability assumption is shown as the dashed lines in Figure 1.

The result on the left side of Figure 6 shows a small decrease in the cost of the all tin-lead and mixed assembly cases, and a considerable increase in the cost of the all lead-free case. The all lead-free case increases in cost because there are more legacy tin-lead parts to be reprocessed. Even if one chooses not to use the legacy tin-lead parts (to avoid the reprocessing cost), excess costs would effectively be incurred due to the loss of the capital invested in tin-lead part stocks that will not be used.

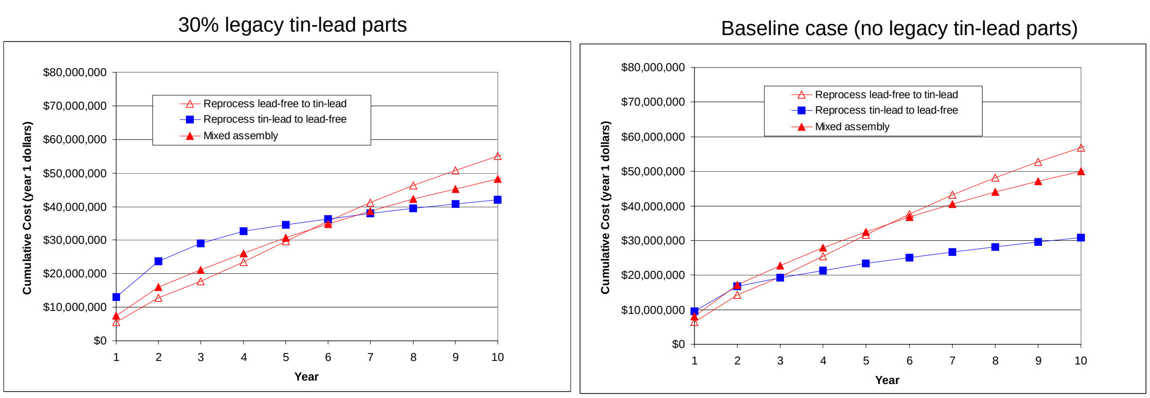

Figure 6 - Effect of tin-lead part availability on cumulative cost for 1 plan. Left = 30% tin-lead legacy parts, Right = baseline part availability profile.

Conclusions

The model described in this paper predicts cumulative and annual costs for three different lead-free part transition management scenarios based on an accumulation of several types of individual costs. For a single plan (where a plan is a unique combination of materials and/or qualification requirements), the conversion to all lead-free parts (reprocessing tin-lead to lead-free when necessary) is the least expensive option after 10 years under every variation considered in this paper. However, when the support of multiple plans is considered other management approaches may be competitive depending on the degree of plan commonality. Irregardless of the management approach, without common agreement on an implementation standard, customers may send mixed signals to suppliers about managing lead-free parts.

Some customers will require the avionics supplier to convert to lead-free on a specific date either with or without the specification of a replacement alloy; and some customers will require the avionics supplier to stay with a tin-lead system for some products. Mixed signals will cost everyone money: 40% plan commonality with $18.5M NRE per plan results in a difference between 1 and 10 plans of $161M (for one supplier). These costs will obviously be passed along to the customer.

References

[1] *Lead-free Electronics*, S. Ganesan, M. Pecht, editors, IEEE Press, John Wiley & Sons, Inc., 2005.

[2] LEAP - Lead-Free Electronics in Aerospace. This project is joint between US avionics groups AIA, ARINC & GEIA. Formed in 2004, it aims to bring US aerospace industry stakeholders together to provide harmonized input into standards and industry guidelines. Coordinator: Lloyd Condra, lloyd.w.condra@boeing.com.

[3] R.J. Coughlin, "Optimization of Spares in a Maintenance Scenario," *Proceedings of the Reliability and Maintainability Symposium*, pp. 371-376, 1984.

[4] P. Sandborn and J. Myers, "Designing Engineering Systems for Sustainability," in *Handbook of Performability Engineering*, K.B. Misra, ed., Springer, 2007.

[5] D. Feng, P. Singh and P. Sandborn, "Optimizing Lifetime Buys to Minimize Lifecycle Cost," *Proceedings of the Aging Aircraft Conference*, Palm Springs, CA, April 2007.