

Cost and production analysis for substrates with embedded passives

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Abstract

With the advent of new materials and technologies that enable passive components to be embedded within electronic substrates, one key question that arises is: under what circumstances (and for what type of applications) is it economically viable to consider using embedded passives? The economic issues that must be considered consist of a combination of manufacturing costs and throughputs, and non-manufacturing life cycle costs. This paper discusses the assessment of manufacturing costs associated with embedding resistors and capacitors in printed circuit boards and provides cost modeling results for an avionics board. The discussion is extended to include optimizing the specific embedded passive content in a board and design for production modeling when embedded passives are present. Life cycle cost issues are also qualitatively discussed.

Keywords

Embedded passives

Cost modeling

Introduction

Economics encompasses an assessment of the total life cycle cost of a design decision where the life cycle includes the design, manufacturing, testing, marketing, sustainment, and end-of-life of the product. The decision to convert discrete passives to embedded passives is more complex than simply reducing the cost of part procurement and paying more for the board. In addition, there are a host of other cost and benefit issues to be considered that translate into life cycle economics at some level.

Embedded passives are fabricated within substrates and, while embedded passives will never replace all passive components, they provide potential advantages for many applications. Possibly the biggest single question about embedded passives is their cost, "...of all the inhibitors to achieving an acceptable market for integral substrates, the demonstration of cost savings is paramount" [1]. There is considerable controversy, however, as to whether applications fabricated using embedded passives will ever be able to compete economically with discrete passive technology. On the bright side, the use of embedded passives reduces assembly costs, shrinks the required board size, and negates the cost of purchasing and handling the discrete passive components that are replaced. However, these economic advantages must be traded off against the higher cost (per unit area) of boards fabricated with embedded passives (a situation that will not disappear over time) and possible decreases in throughput and yield of the board fabrication process.

The application-specific costs depend on many effects when embedded passives are present in a board:

- Decreased board area due to a reduction in the number of discrete passive components
- Decreased wiring density requirements due to the integration of resistors and bypass capacitors into the board
- Increased wiring density requirements due to the decreased size of the board
- Increased number of boards fabricated on a panel due to decreased board size
- Increased board cost per unit area
- Decreased board yield
- Decreased board fabrication throughput
- Decreased assembly costs
- Increased overall assembly yield
- Decreased assembly-level rework.

Several other less obvious recurring system costs may also be affected by the use of embedded passives, for example: the need to electromagnetically shield the board may be reduced or eliminated when certain passives are embedded (saving on expensive materials and their assembly), and the costs associated with thermal management of the board may also be affected.

Due to the opposing nature of many of the effects listed above, the overall economic impact of replacing discrete passives with embedded passives is not trivial to determine and, in general, yields application-specific guidelines instead of general rules of thumb.

Fabrication and manufacturing cost modeling

Several previous efforts have addressed cost analysis for embedded passives and thus provide varying degrees of insight into the economic impact of embedded passives. The target of all these economic analyses is to determine the effective cost of converting selected discrete passive components to embedded components. The most common approach to economic analysis of embedded passives is to: 1) reduce the system cost by the purchase price and conversion costs¹ associated with the replaced discrete passives, 2) reduce the board size by the sum of the layout areas associated with the replaced discrete passives and determine the new number of boards on the panel (number-up), and 3) determine the new board cost based on a higher per unit area cost for the embedded passive panel fabrication and the new number-up computed in step 2. The results of these three steps determine the new system cost.

Brown [2] presents an outline of all the potential contributions to the life cycle cost of embedded passives. Rector [1] provided the economic analysis using the first-order approach outlined above. Ohmega Technologies Inc. has also generated a cost model for assessing cost tradeoffs associated with its Ohmega-Ply[®] embedded resistor material, [3]. The Ohmega cost model follows the first-order approach described above, and includes yield and rework effects. Realf and Power, [4], developed a cost model for board fabrication and assembly associated with embedded resistors. The model includes test (board and assembly), yield, and rework. Power *et al.* [5] extend the model in [4] to embedded capacitors and cast it in the form of an optimization problem targeted at choosing which discrete passives to integrate based on an assumption of assembly and substrate manufacturing process details, and material properties. Another analysis that recently appeared, focused on design tradeoffs for a GPS front end, [6]; this analysis includes detailed cost modeling of thin-film embedded resistors and capacitors.

The results included in this paper were generated using a manufacturing cost model from Sandborn *et al.* [7, 8], which includes the analyses performed in the previously referenced models and incorporates quantitative routing estimation and assesses board fabrication throughput impacts for setting profit margins on board fabrication.

Avionics cost tradeoff example

An example size/cost tradeoff analysis has been performed on an avionics board. The conventional implementation of the board is 2.91 x 5.87 inches and has 10 layers. There are 54 embeddable resistors and 59 embeddable bypass capacitors. In the baseline version of this board (low-volume production), the discrete passives are expensive, resistors ranging from \$1.02 to \$4.20 each and the bypass capacitors costing \$0.48 each. An identical board (high-volume production) with all discrete passives priced at \$0.05 each has also been considered. Figure 1 shows the results of embedding various quantities of the resistors in both versions of the board (capacitors are not embedded in Figure 1). Relative system cost is plotted in Figure 1 and throughout this section indicating the system cost less the cost of all non-embeddable components and functional testing. Two types of embedded resistors are considered, additive resistors formed by plating or printing resistor material directly onto innerlayer pairs that are used for routing, and subtractive resistors formed using dedicated resistor layer pairs, e.g., Ohmega Ply. For example, the specific solution (data points) in Figure 1 indicate that boards fabricated using a subtractive may become economical when the first resistor is embedded, while a greater number of resistors must be embedded when using subtractive technologies (for the low cost discrettes, the subtractive technology never reduces manufacturing cost for this application). Figure 1 also clearly shows the obvious result that when the discrete passives cost more, embedded passives become practical more quickly. An important note, Figure 1 does not address other performance, tolerance, or reliability issues that may preclude the use of an additive technology.

The resistor results appear as a “band” in Figure 1 due to uncertainties in the impact on the wiring (routability) of embedding

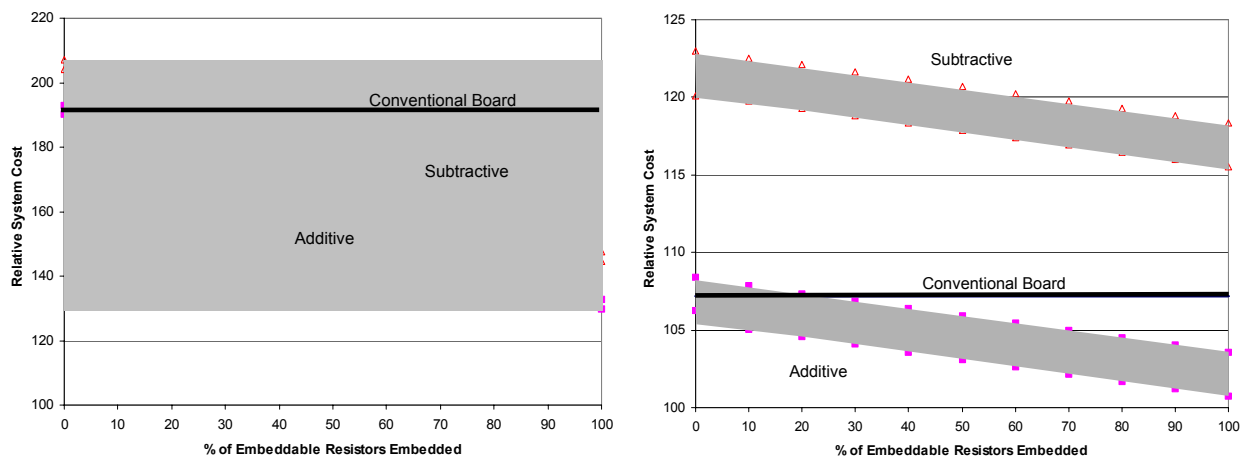


Figure 1 - The cost of embedded resistors for the avionics example board. The left figure represents the baseline case (high-cost discrete passives), the right figure is the high-volume assumption (low-cost discrete passives). The conventional board solution has all discrete passives, no capacitors are embedded in these cases. Only resistors ≤ 10 Kohms were considered embeddable.

¹ Conversion costs are the handling, storage and assembly costs associated with a discrete component.

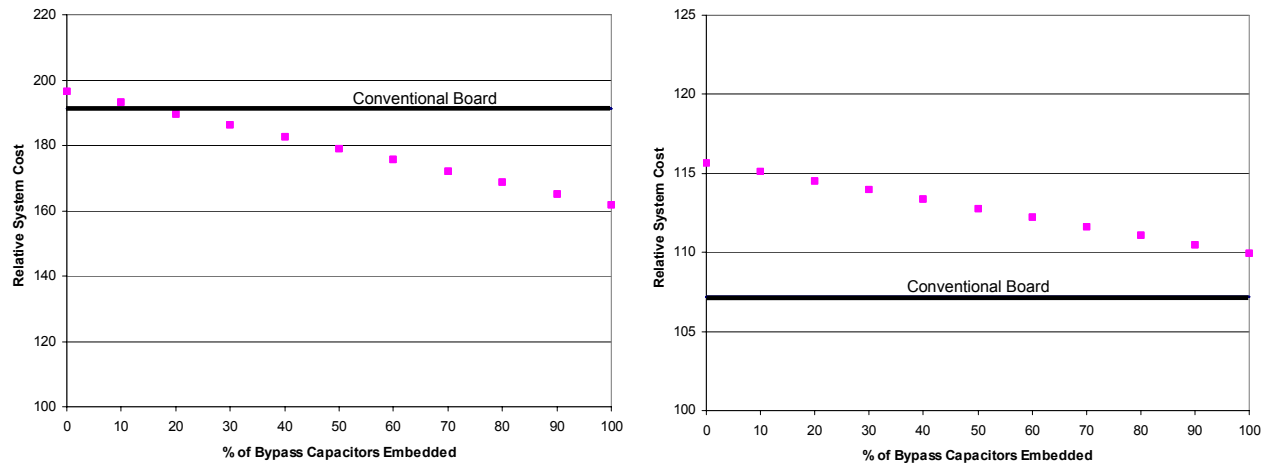


Figure 2 - Capacitor embedding for the picocell board application. The left figure represents the baseline case (high cost discrete passives), the right figure is the high-volume assumption (low cost discrete passives). The dielectric material for embedded capacitor construction was assumed to be $\$0.0104/\text{in}^2$. Only capacitors ≤ 100 nF were considered embeddable.

resistors. The upper edge of the bands represent the assumption that the conventional board used all available routing resources and that decreasing the wiring resources needed by the application a small amount (due to embedding resistors) will not decrease the required layers. The lower edge of the band represents the assumption that the conventional board did not use all of the available routing resources and that a decrease in the wiring resources needed by the application (even by a small amount) may reduce the number of layers required in the board. Practically speaking, solutions start at the top edge of the band (10 layers for the example board) and may step down to the lower edge of the band (8 layers) at some point. Other types of step discontinuities can also appear in the results if the board shrinks in size enough so that more boards can be fabricated on a panel (number-up increase), or if allowing the board size to shrink drives the solution to add layer pairs to satisfy wiring demands, see [7] and Figure 4 for additional examples.

Next consider the integration of capacitors. Figure 2 shows the relative system costs as capacitors are embedded (none of the embeddable discrete resistors are embedded in Figure 2). Since embedding of bypass capacitors minimally requires material replacement, the very first bypass capacitor embedded increases the cost of the board dramatically, but as more capacitors are embedded, the added cost of the replacement material layer is gradually offset by the avoidance of discrete capacitor part and assembly costs. As with the embedded resistors, it is obvious from Figure 2 that the higher the cost of the discrete capacitors being replaced, the more economical embedding capacitors becomes. However, the right side of Figure 2 points out that making a solely economic case for embedding capacitors is difficult for most applications.

The economics of embedded bypass capacitors can be generalized by observing the application-specific embeddable capacitor density necessary to breakeven on costs, i.e., by plotting the embeddable capacitor densities where the cost difference between the conventional and embedded passive implementations is zero. Figure 3 shows the general result for several previously published applications (see [8]) and the avionics example considered in this paper. The critical assumptions for this plot are: the board size and the number of layers required for routing is not allowed to change. Note, Figure 3 corresponds to $\$0.05/\text{discrete capacitor}$ in all cases. The primary differentiator between the applications as far as this plot is concerned is the panelization efficiency (the total board area on the panel divided by the panel area). The dielectrics used to produce embedded capacitor layers are relatively expensive and would be purchased and used at the panel size, therefore, a low panelization efficiency indicates that the application is wasting a lot of the expensive material, versus a larger panelization efficiency indicates less waste and therefore lower breakeven capacitor densities are possible.

Optimizing embedded passive content

Due to the large number of decision variables and the complexity of the optimization function, it is advantageous that some type of optimization method be implemented to determine the optimal set of discrete devices that should be embedded. A methodology that employs genetic algorithms coupled with the cost model in [8] has been developed to aid in the identification of the optimum mix of passives to embed on an application-specific basis (the model only minimizes manufacturing cost, i.e., it does not consider performance or reliability issues).

A genetic algorithm is a stochastic, directed and highly parallel search technique based on principles of population genetics. It is a powerful method for solving combinatorial problems with discrete variables and discontinuous functions. A genetic algorithm approach was selected because it is a powerful method for solving combinatorial problems with discrete variables and discontinuous functions. The ability to treat discrete variables and complex functions without derivatives is advantageous and promising for solving the embedded passive design problem since it includes discrete variables and has a complex and ambiguous evaluation function.

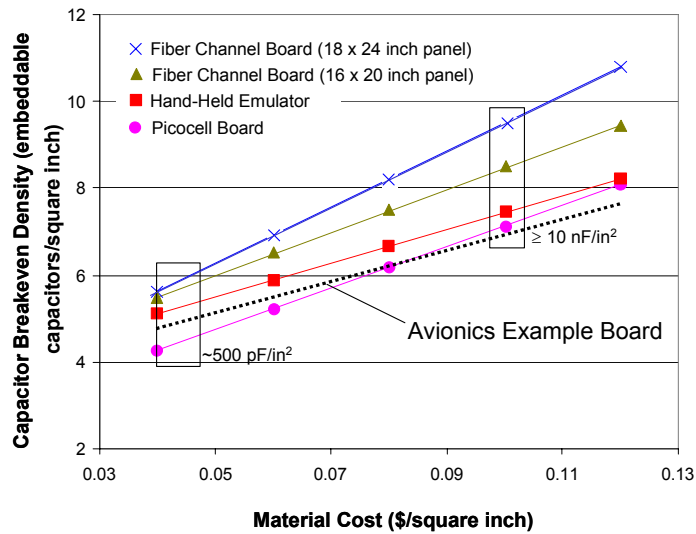


Figure 3 - Bypass capacitor breakeven densities as a function of dielectric material replacement costs. Only single layer substitution is considered in this plot. All results are for applications where discrete capacitors cost \$0.05 or less each.

Figure 4 shows the effects of embedding resistors on the board price for a 5.1 x 15.24 cm board respectively with a 500 discrete resistors of type 1 and 400 discrete resistors of type 2. Figure 4 indicates that the optimal board price is realized at approximately 52% of embedded resistors. Note, this example shows the minimum board price, not system cost, which may be a minimum at a slightly different mix of embedded passives.

Applying design for production principles to embedded passive substrate manufacturing

The economic impact of embedding discrete passives includes not only the material and direct manufacturing cost (as discussed above) but also manufacturing system performance measures (such as cycle time, resource utilization, inventory, delivery performance, and capacity) and their associated costs. Although manufacturing system performance issues are usually considered only as a manufacturing planning and control issue, it is clear that product design affects these factors (just as product design affects

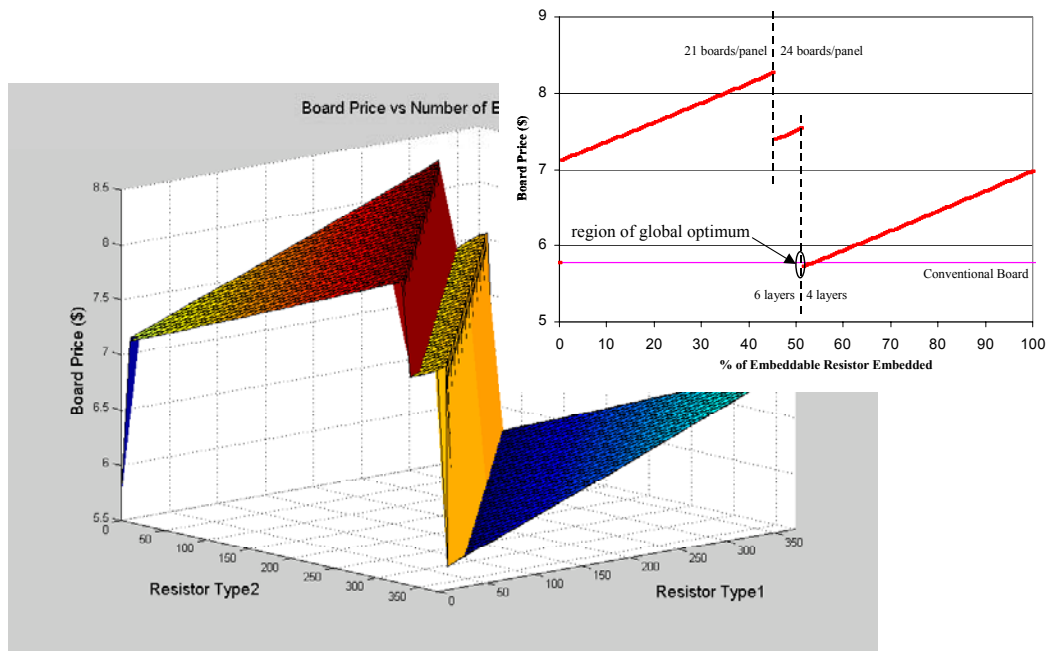


Figure 4 – Surface plot showing all board price solutions for embedding two different types of resistors. A genetic algorithm automatically searches this space for the lowest cost solution. The plot in the upper right shows a diagonal cut through the surface. other life cycle considerations).

Design for production (DFP) is a collection of techniques for evaluating the impact of a product design on manufacturing system performance [9, 10]. These methods require information about a product's design, process plan, and production quantity along with information about the manufacturing system that will manufacture the product. Most of the work has been in three areas of DFP: design guidelines, capacity analysis, and estimating manufacturing cycle time. The manufacturing system of interest may be a production line, a factory, or a supply chain. Unlike design for manufacturing or design for assembly, which evaluate direct manufacturing costs and time, DFP considers systems-level issues.

To apply DFP principles to embedded passive substrate manufacturing, it is important to distinguish between two manufacturing scenarios. In the first scenario, the manufacturing system is making essentially a single, high-volume product (or a small number of high-volume products). In the second scenario, the manufacturing system is making a variety of customer-specified products in a make-to-order manner.

Single product scenario. In this scenario, the problem is to evaluate the relevant manufacturing system performance measures as a function of one product's design parameters. Then, as necessary, the design parameters can be changed to improve the manufacturing system performance. In particular, DFP techniques can determine how changing the number of embedded passives impacts manufacturing cycle time (also known as throughput time). The total manufacturing cycle time, which is the time between the release of a job and its completion, is the sum of the manufacturing cycle times at each of the workstations that jobs must visit. The manufacturing cycle time at a workstation depends upon the amount of time jobs spend waiting for processing and the average job processing time.

The addition of any embedded passives requires changes to the sequence of operations used to make a printed circuit board. In addition, depending upon the application, embedding more passives may reduce the processing requirements at some operations but while increasing them at other operations. Due to this complexity, it is necessary to develop models for specific applications and manufacturing systems.

Chincholkar and Herrmann [11] present a DFP model for evaluating manufacturing cycle time as a function of the number of embedded passives. This model first determines how the number of embedded passives affects the number of layers, the board thickness, the board area, the number of boards per panel, and the number of holes. The model then estimates the mean processing times at each step and the total manufacturing cycle time. When applied to a specific case, the model showed that increasing the number of embedded passives reduced the resource utilization and congestion at the three busiest workstations. Thus, the total manufacturing cycle time decreased.

Multiple product scenario. For the multiple-product, make-to-order scenario, changes to a single product design will have a small impact on manufacturing system performance. Moreover, since the specifications vary from one order to the next, the manufacturing firm cannot optimize the designs ahead of time. Instead, the firm uses design rules to translate customer specifications into final designs. While some design rules describe physical constraints that cannot be violated, others are recommendations for achieving cost-effective production. Among these, there must be a set of design rules that determine which resistors to embed, which nonbypass (nonelectrolytic) capacitors to embed, and whether or not to embed bypass capacitors. Design rule modifications affect all of the orders that arrive and thus may significantly change manufacturing system performance.

To evaluate design rules, it is necessary to have information about what future customers are likely to require. The design rules translate customer specifications into final designs. Thus, it is possible to determine the characteristics and processing requirements that future jobs are likely to have. Then, it is necessary to verify that the design rules lead to processing requirements that do not exceed the available manufacturing capacity. Finally, one can estimate the following expected costs: direct manufacturing cost, the work-in-process inventory cost, and the tardiness cost. (These costs are also affected by issues such as lead time and the available manufacturing resources, which design rules do not influence.)

Determining these costs requires a model that can estimate manufacturing system performance measures as a function of the design rules selected. This allows firms to identify cost-effective design rules that lead to good manufacturing system performance. To illustrate the use of this approach, the authors are currently applying a model of this type to a set of typical distributions for discrete passives [12].

It is important that a manufacturing firm understand how the embedding decision affect the manufacturing performance. Having this feedback early avoids iteration needed to solve problems of manufacturing capacity, response time, or other system performance. DFP models can help a firm collect this information. A firm should apply models like those described here to the specific system that they will use and should incorporate their results with other information about the cost, performance, reliability, and desirability of embedding passives.

Life cycle cost impacts

In the previous section we only considered system manufacturing issues. This only represents a portion of the economic impacts of converting discrete passives to embedded passives. Life cycle effects, which for many applications will dominate manufacturing costs, include all other activities associated with the product. Generally speaking, life cycle effects are more difficult to quantify into costs than manufacturing activities. The following life cycle activities are among those that embedded passives will impact:

Design Costs – Costs of engineering and other technical personnel to design boards that include embedded passives. If designers require specialized training, or new CAD and/or other specialized design tools to successfully perform embedded passive board design, then the costs of these activities must be considered. A summary of the design tool requirements for embedded passives is included in the NEMI 2002 Industry Roadmap, [13]. One must also consider costs associated with effort and tools for design verification and functional test development. Extra design costs may also include libraries of models for embedded passives ranging

from symbol libraries to high-performance RF models for use in electrical simulation. The inclusion of embedded passives may also affect the degree to which a design can be reused and upgraded (re-design costs). Also included in the design costs are prototyping costs. Are embedded passive applications going to require additional prototype boards?

Non-Recurring Costs – To what extent will embedded passives require board fabricators to invest in new equipment (see [4] for an equipment analysis)? Equipment is not the only non-recurring cost that may be associated with embedded passives. There will be additional tooling (artwork) for layer pair production, potentially additional chemistry to be managed in the board fabrication process, and finally licensing fees and royalties may have to be paid for the use of technology, material, and/or processes.

Time-to-Market – Does the design, verification, and prototyping of embedded passive boards require more calendar time than that for conventional systems? Delays in time-to-market for a new product of weeks or months can cost substantial money and in some cases mean missing the market for the product completely.

Performance Value – Embedded passives may result in size or performance improvements in a system that enable increases in market share for the manufacturer. It may be the case that for some quantifiable increase in system cost, a manufacturer can differentiate itself from its competition by providing a product that is lighter, smaller, faster, more reliable, or with greater functionality than its competition, and the customer is willing to pay extra for one or more of these improvements.

Qualification and Certification – The introduction of new materials and processes into board fabrication requires material providers and board fabricators to assess and possibly update safety certifications, e.g., UL Certification. While the cost of this type of certification is not directly borne by the users of embedded passives, it will be reflected in the board costs. On the other hand, there will be a reduction in the costs associated with qualifying discrete component manufactures.

Liability – Embedded passives, or any new technology, material, or process may carry with it unforeseen financial liabilities. The liabilities may be in the form of causing injury to customers, employees of the manufacturer, or the environment. Long-term studies of the effects of the materials and the processes used to incorporate them into boards may be necessary to prove or disprove liability claims.

Sustainment – Sustainment is a collection of many activities all of which have an economic impact. In general, sustainment is all the activities necessary to:

- Keep an existing system operational (able to successfully complete the purpose it is intended for);
- Continue to manufacture and field versions of the system that satisfy the original requirements;
- Manufacture and field new versions of the system that satisfy evolving requirements.

The foremost concern with embedded passives is reliability. Conventional wisdom is that system reliability will improve because of the reduction in the number of solder joints, however, this will only be realized if the reliability does not commensurately decrease due to other embedded passive specific effects. Reliability questions arise from two origins: first are the specific embedded structures as reliable or more reliable than the rest of the components and packaging? Secondly, are there embedded passive specific processing conditions (during board fabrication) that remove life from other conventional board structures? Changes in system reliability appear either as warranty costs (replacement) or as maintenance costs (repair).

For systems that are subject to repair, embedded passives may change the ease with which problems in the system can be diagnosed, physically repaired and retested. In turn, if the faulty board is to simply be replaced, its reliability impacts the number of “spare” boards that must be manufactured to fulfill expected replacement commitments.

Sustainment, however, goes further than reliability driven replacement and repair. Sustainment also means that the system should remain manufacturable through the end of its support life (to fulfill additional requirements for new product and spare replenishment). This is not generally difficult for manufacturers of laptop computers and other short-life consumer products, but is a huge concern (and cost issue) for long-life products such as avionics for aircraft. The biggest component related problem that long field life systems see is obsolescence (particularly electronic part obsolescence), [14]. Most electronic parts have short lifetimes (from an availability perspective) relative to even the design cycle of an aircraft, let alone an aircraft’s support life. For systems like aircraft, qualification and certification requirements may make simple substitution for obsolete parts with newer parts prohibitively expensive. Embedded passives will mitigate some obsolescence problems by replacing discrete parts that would become obsolete. On the other hand, if the materials used to manufacture the embedded passives within the board become obsolete, i.e., replaced by newer materials, the overall obsolescence problem may well become much worse.

Environmental and End of Life – The fabrication of passives within boards obviously increases the volume of waste produced during the board fabrication process. Disposition of board fabrication waste is a significant contributor to the price of boards. If any of the embedded passive specific contributions to the waste stream are considered hazardous then the waste disposition costs could increase. Waste disposition is also a factor at the other end of the life cycle, i.e., at end-of-life. Depending on the type of product that the embedded passive board is being used within and the location in the world where the product is being sold, the manufacturer may bare some or all of the cost of disposing of the product when the consumer has finished with it.

Financial – Several costs associated with creating and holding inventory (handling, storage, procurement) associated discrete passives are potentially avoided, this includes the cost of money that is invested in stored passives as opposed to invested elsewhere.

SUMMARY

An overview of cost modeling efforts associated with embedded passives has been provided. More extensive example analyses performed with the models discussed in this paper are available in the references, e.g., [7, 8]. It can not be overstressed that the opposing nature of many of the effects associated with embedding passives in printed circuit boards makes the overall economic impact of replacing discrete passives with embedded passives a non-trivial economic tradeoff to perform and that application-specific analyses need to be performed to determine the economic viability of such a conversion.

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