Printed Circuit Board Materials: An Evaluation of Manufacturing Technologies and Market Requirements

by

Ng, Lee Hong

Bachelor of Science in Mechanical Engineering with Highest Honor
The University of Texas at Austin (1986)

Master of Science in Materials Engineering
Massachusetts Institute of Technology (1988)

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Signature of Author ______________________________
Department of Material Science and Engineering
January 12, 1990

Certified by ______________________________
Professor Joel P. Clark
POSCO Professor of Materials Engineering
Thesis Supervisor

Accepted by ______________________________
Professor Linn W. Hobbs, Chairperson
Departmental Committee of Graduate Students

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Abstract

A methodology for evaluating material competitiveness for printed circuit boards has been developed. The methodology combines the evaluation of performance requirements with economic consideration through the use of multi-attribute utility analysis and technical cost modeling. The demand for new materials are assessed using a demand model based on a markov chain. The markov chain relates future market share to past materials usage and the probability of switching. The probability of switching is estimated from measured utility using the logit model.

The methodology was applied to two case studies in the PCB industry. In the first case study, materials selection for backpanels in the computer and communications industry was analyzed. The analysis found that the computer industry favors high Tg materials such as polyimide and BT, while the communications market prefers low cost materials such as epoxy-glass. Among the new materials targeted at high performance PCBs, cyanate ester has the greatest potential, but its market success will depend on its pricing policy and manufacturing requirements.

The second case study analyzed the material options for housing a digital processor using the Standard Electronic Modules (SEM) in "E" format. The analysis include both ceramic and organic PCBs on both high and low CTE cold plates. The results indicated that the epoxy-Kevlar on aluminum system is the most attractive alternative. However, new alternatives can become competitive with slight improvements in performance. For example, if the dielectric constant of ceramic system can be reduced to 6.0, it will become competitive with the epoxy-Kevlar system. Similarly, cyanate ester, Al/Graphite and Al/SiC systems are competitive at certain price and performance levels.

Thesis Supervisor: Professor Joel P. Clark
POSCO Professor of Materials Engineering

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I dedicate this thesis to my parents, Ng Kim Tian and Koh Bee Seok.

INTRODUCTION

Background

The transistor is one of the most important inventions of the 20th century. It is this invention, and the later development of integrated circuits (IC), that propelled civilization into the information age where a large amount of information can be stored or transferred within a small area at an ever-increasing speed. The stimulus behind the information age is IC technology. As developments in IC technology continue to drive toward higher speed and smaller size, it is the packaging of these microelectronics devices that may ultimately limit the systems performance. Figure 1 shows the percentage of system delay due to packaging as a function of system speed. At system speeds above 100 Mhz, packaging may account for more than 50% of the total system delay [1]!

In the early days of electronics, groups of circuit components were interconnected by discrete wiring. When vacuum tubes were replaced by transistor, the reduction in power consumption and weight allowed the mounting of these components onto printed circuit boards (PCB), a concept which is still used today. The edge of a PCB can also be made into pluggable connectors when a large number of PCBs must be employed to assemble a system. This system of packaging provides the basis for organizing complex electronic circuits, as well as forming the basis for modular design and replacement schemes. Figure 2 illustrates the evolution of electronic circuits and its impact on packaging.

The development of IC with small and fragile connections requires that the IC, commonly referred to as the chip, be encapsulated for mechanical support and protection against the environment. With this packaging requirement, the three tier packaging architecture shown in Figure 3 evolved.

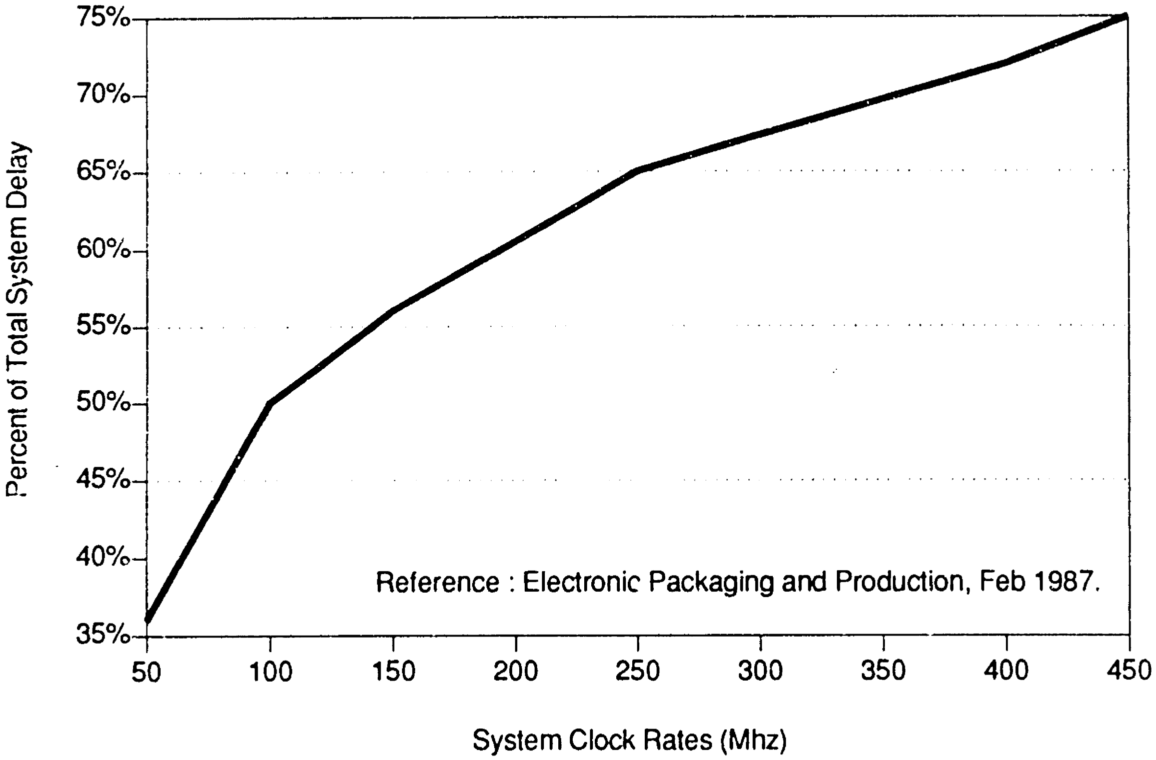


Figure 1: Percentage of Total System Delay Due to Packaging

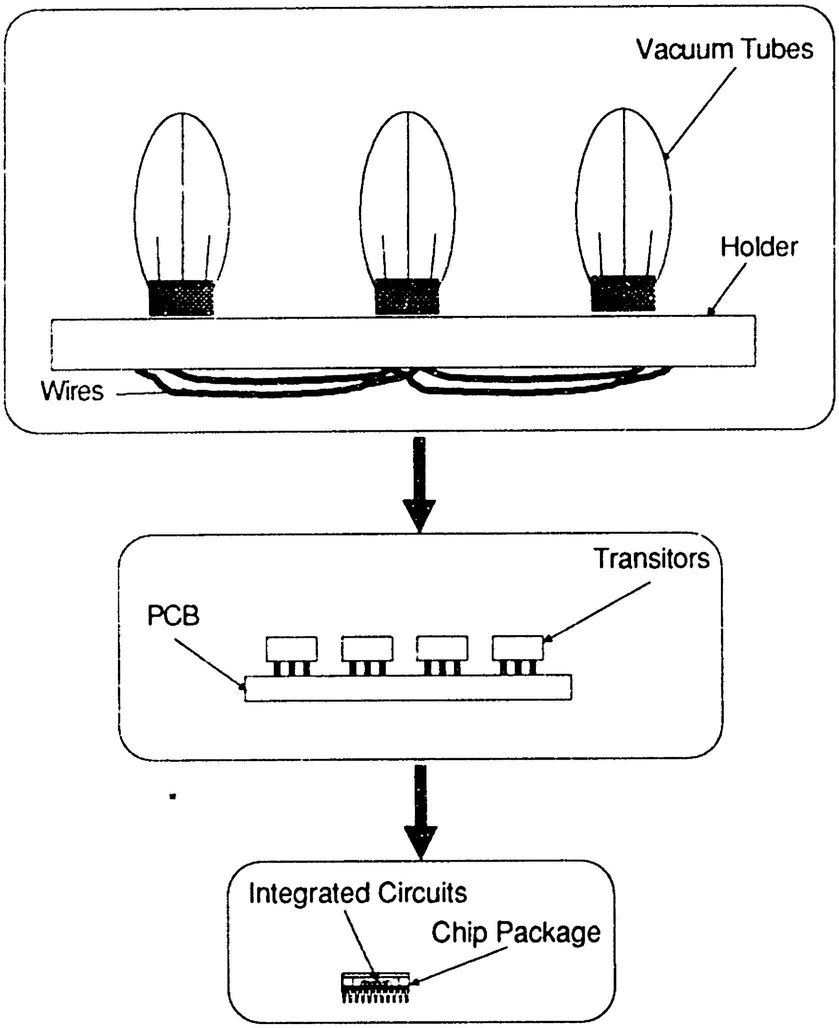


Figure 2: Evolution of Electronics Packaging

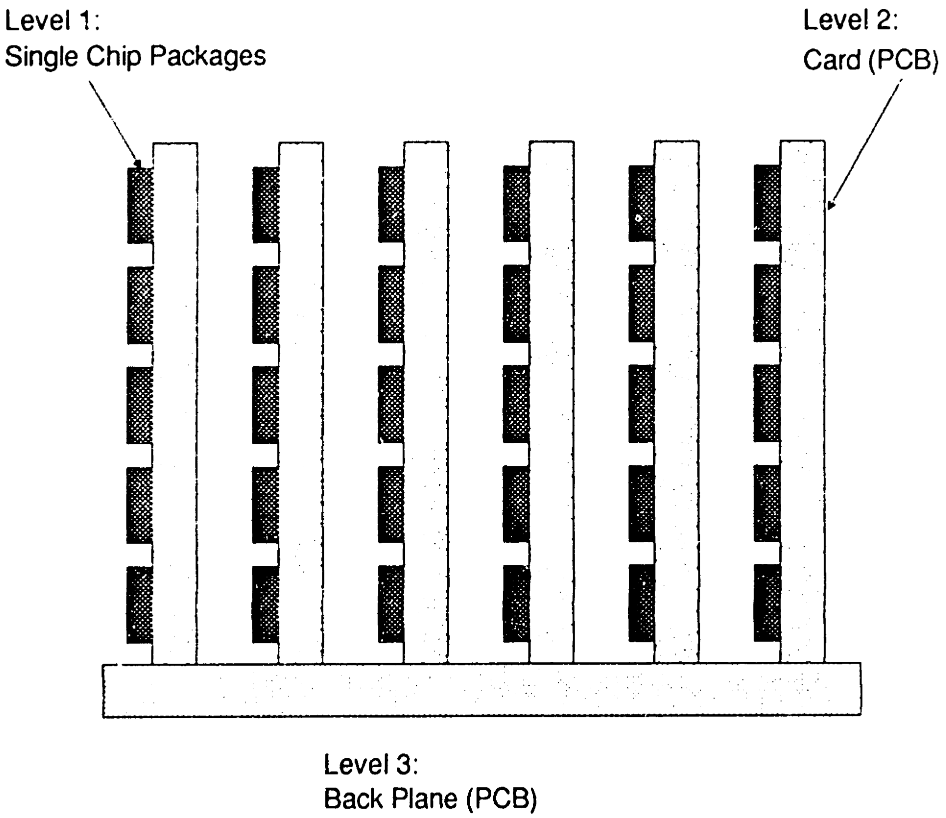


Figure 3: Conventional Three Tier Packaging Approach

In the three tier packaging architecture, the first level of packaging is that of the single chip package which contains the IC. The next level of packaging is the PCB which provides connections for the chip packages, and the third level is called the backplane, which may also be a PCB, but has connectors for the PCBs to be mounted.. Each level presents its own unique engineering challenges in design, materials, and manufacturing.

As IC technology developed, the packaging system was called upon to perform more and more functions: provide environmental protection to the microelectronic devices, dissipate heat generated by the devices and distribute power and signal to the devices [2]. In addition, the packaging system must facilitate repair and testability. All these requirements put demand on the packaging materials. To support the progressive advancement in IC technology, limitation in packaging materials [3], as well as the interconnection technology, must be overcome.

Performance Requirements of Electronic Packaging Materials

Materials must possess several performance characteristics in order for them to be a candidate for electronic packaging. In information processing, information is processed as a result of signal (voltage) changes from one value to another. The transmission of these signals does not occur instantaneously; their speed is dependent on the physics of electromagnetic wave and the type of materials used to construct the circuit according to the following relationship:

$$V = C / \sqrt{E}$$

Where V = Speed of signal in m/s
C = Speed of light in m/s
E = Effective dielectric constant of the medium

A signal (transmission) line is usually made up of two parts: a conductor for signal transmission and an insulating environment to isolate the signal lines. Three electrical parameters are considered vital to the performance of a circuit: capacitance, inductance and resistance. All materials have a certain capacity to store electrical charges when a voltage is applied. This capability is called the capacitance. To change the voltage in the circuit, the amount of charge stored in the materials must be changed by the flow of current. Thus, the higher the capacitance of the line, the longer it takes to change the voltage, and the slower the system speed. The signal line capacitance is directly proportional to the length and cross-sectional geometry of the signal line, as well as the dielectric constant of the insulating medium.

The dielectric constant of an insulating material is defined as the ratio of the capacitance of the medium to that of vacuum (in most practical cases, the capacitance of air is used). It is a fundamental property of materials which results from the alignment of dipoles within the insulator in the direction of the applied field [4]. Its value, however, is not a constant, but a function of crystal orientation, frequency of the signal, and environmental conditions such as temperature and humidity. When an insulator is used to isolate signal lines, it separates regions of different electrical potential and therefore, charges are stored in the material. Subsequently, when the electrical potential changes due to signal transmission, these charges will slow the transmission of signal. At the same time, energy is lost as heat in the material as the signal propagates. This irreversible power loss is proportional to dielectric constant and the dissipation factor. Thus, a low dielectric constant and dissipation factor material is preferred.

In addition to the capacitance effects, a change of voltage also generates a magnetic field. This magnetic field causes current to be induced in the current carrying lines, as well as other signal lines around it. The induced current opposes the original current and slows the signal travel. This is called the inductive effect. The inductance of a circuit is a function of the magnetic strength of its surrounding materials and the its geometry. The most detrimental effect of inductance is the currents induced in the neighboring lines which may trigger false signal. This cross-coupling noise is a function of inductance and dielectric constant of the medium.

Unlike the capacitive and inductive effects, the resistance of a circuit is present in all materials when a current is passing through the circuit. It is a result of the movement and interaction of electrons within the atomic structure in the presence of a potential difference. The electrical resistivity of a conductor depends on its temperature, materials and geometry. The resistive effect of a circuit results in energy loss, which usually appears as heat.

In electronic packaging, heating and cooling of the packaging system occurs continuously due to the external environment, as well as internal power cycling. Therefore, it is important that the all the packaging materials expand at the same rate to prevent stresses from building up in the interconnections. Theses stresses may result in premature failure of the interconnections. To minimize these stresses, the coefficient of thermal expansion (CTE) of the different packaging materials must be closely matched to each other. CTE is a measure of the rate at which a material expands as its temperature increases. CTE matching is especially important if the package size is large. Another important thermal consideration is the thermal conductivity of the packaging materials. As electrical system continues to miniaturize, heat removal from the chip becomes more critical as the increased heat generated by the chip must be dissipated within a smaller area. The heat must be removed to prevent overheating of the chip, which may result in chip failure.

Thus, the selection of materials for electronic packaging is not a simple matter of optimizing electrical performance. Other factors such as heat dissipation, mechanical strength and reliability play a key role in the performance of the system and must be considered as part of the total electronic system. These factors may not be pure material properties, but may be affected by packaging design (geometries) and interconnection technologies. Moreover, the packaging materials must work within the constraints of the interconnection technology. The next section is a short review of interconnection technology.

Review of Interconnection Technology

At the dawn of IC technology, the interconnection technology was highly dependent on the level of packaging. At the first level of packaging, the chips are housed in a ceramic or plastic package. Plastic packages are used extensively in the commercial industry due to their lower cost. On the other hand, ceramic packages are used mainly in the military and high performance applications due to their superior performance and higher cost. Electrical connection between the chip and the package is achieved through the soldering of a thin wire between the pads on the chip to that on the package. This technique is known as wire bonding. Connection to the next level of packaging (PCBs) is by pins on the package that fit into corresponding holes on the PCBs. Solder may be applied to the connections to enhance electrical performance.

As the integration at the chip levels increases from small scale integration (SSI) to large scale integration (LSI) and now to the very large scale or very high speed integration (VLSI or VHSI), the number of interconnections (I/O connections) required from the chip to the outside world increases exponentially as indicated by Rent's rule [5]. This stimulates the development of new interconnection technologies at all levels of packaging. In some cases, an entire level of packaging may be eliminated to achieve higher packaging density.

For chips with a large number of I/O connections, tape automated bonding (TAB) and flip chip (also called "solder bump" or Controlled Collapse Chip Connection, abbreviated as C4) are two alternatives. In TAB, instead of using wires for the chip-to-package connections, metal beams of copper and tin are laminated onto a polyimide tape. which is bonded onto the chips. The chip is then bonded onto the pads on the package by solder processes and the tape is removed after bonding. The main advantage of TAB is its small pitch, adaptability to automation and testability [6]. Both wire bonding and TAB are currently in peripheral scheme where connections are only made at the peripheral of the chip, but TAB is projected to have area array possibilities.

Flip-chip or solder bump bonding uses solder bumps deposited on an area array on the chip and a matching footprint of solder on the substrate. The area array allows the number of I/O connections to increase as the square of the chip dimension. In flip chip, the upside-down (flip chip) is aligned to the substrates and all the joints are made simultaneously by reflowing the solder. Because all the bonds are done at the same time, flip chip bonding has the potential of being the lowest cost alternative. Furthermore, flip chip bonding will allow true reworkability [7], which is important for expensive high integration chips.

At the second level of packaging, where the package is mounted onto the PCB, changes are also taking place. The use of pin-through-holes results in inefficient use of PCB real estate when the number of interconnections is very high, since the holes take up valuable space which could be used for signal lines. Poor electrical performance also results from the long signal lines and parasitic capacitance at the connections. To overcome these deficiencies, surface mount technology (SMT) was developed. In SMT, the chip packages are soldered directly onto the pads on the surface of the PCB, thereby eliminating the needs for holes on the PCB for the pins. This not only saves board real estate, but also results in better electrical performance [8].

In response to the ever-increasing number of I/0 connections from high integration chips, many designers have begun to deviate from the traditional packaging approach of packaging single chips and attaching them onto a PCB. One popular approach is "multichiping" where two or more chips are mounted onto a substrate using wire bonding or other chip attachment techniques described earlier [9]. The substrate can be organic or ceramic, or a combination of both. In all cases, it has a higher packaging density than PCBs. The multichip module may then be plugged onto a PCB or backplane.

Another approach is chip-on-board (COB) where the chips are directly connected to pads on the PCBs by wire bonding or TAB. The connected chip is then covered with a "blob" of material, usually epoxy, to protect it from the operating environment. This technique is especially common with low cost consumer electronics, but it is beginning to be used in other commercial products [10]. The main advantage of this technique is the elimination of one level of packaging, but reliability remains an issue. An additional constraint is that the available circuit density on the PCB is insufficient to accommodate the circuit density required when LSI chips are directly mounted onto the board.

Summary

The goal of greater miniaturization and improved performance of electronic equipment is placing more and more stringent performance requirements on packaging materials. Some of these performance requirements include enhanced heat dissipation, minimum thermal stresses, good dimensional control, and processing feasibility, many of which are not classically associated with "electronic" materials. The selection of materials for packaging will become an increasingly important dimension in the performance of electronic systems. Therefore, an understanding of the criteria for material selection and technology interactions will provide the first step towards the design of better electronic system.

PROBLEM DEVELOPMENT

Introduction

Despite best research efforts into other interconnection technologies, such as multi-chiping and chip-on-board, these technologies will take a few years to mature. Thus, the conventional method of packaging single chip in packages and mounting them onto printed circuit board (PCB) will prevail in the next few years [11]. The introduction of surface mount technology (SMT) has set a new standard for packaging single chips. This has resulted in improved performance and higher density at the chip level. The next logical step is to focus on PCB technology with regard to the needs of SMT. PCB technology is expected to play a major role in the overall improvement of electronic system performance in the future [12]. Moreover, if multi-chiping were to become the industrial standard in the future, improved PCB technology will continue to be important.

Traditionally, a printed circuit board is a planar interconnection systems for packaged chips, with "printed" copper circuitry. It may be rigid, flexible or "rigid-flex", which is a combination of rigid and flexible boards bonded together. More recently, the definition of PCBs has been broadened to include non-planar, injection molded (3-D molded) boards with circuitry added in a separate step. 3-D molded boards are made with thermoplastics materials and usually have connectors or housing directly molded into the boards. In 1987, the U.S. PCB industry consumed $1.34 billion of chemicals and plastics and the number is expected to reach $2.3 billion by 1991 at an annual growth rate of 14.5% [13]. Of the $1.34 billion, $730 millions were spent on board laminates.

Because of the strategic importance of PCB, the industry has attracted a lot of attention and research dollars. The acceptance of SMT in the electronics packaging industry has created an impact on the PCB industry by demanding higher circuit density from the PCB. The increase of PCB circuit and device density, however, has been accompanied by heat dissipation and thermal stress requirements. This has led to ever-increasing pressure upon the performance and fabrication technologies associated with PCBs.

PCB manufacturers have not only looked to developments in processing technology, such as multilayer boards and fine line technologies, but also to new materials to meet the performance and processing requirements of high density PCBs. However, since the electronic resin market is such a small fraction of the total market for plastic resins (about 1.5% of total plastic shipments [14]), the rate at which new materials are introduced for PCBs has been slow. Nevertheless, current developments in surface mount technologies (SMT) have been accompanied by the recent introduction of new material candidates, such as cyanate ester, and the resurrection of older systems such as ceramics, for PCB applications.

Important Performance Characteristics of PCB Materials

A PCB is a composite structure consisting of conductors embedded in an insulating medium. Planer (organic) PCBs are manufactured from laminates consisting of three parts: resin, reinforcement and copper. The resin serve as the insulating material for the copper conductors. The fiber reinforcement provides mechanical strength to the organic resin and controls the dimensional stability and the coefficient of thermal expansion (CTE) of the laminate. The suitability of a material system for PCB applications depends critically upon the electrical, structural and thermal characteristics of the composite.

The electrical requirements of the conductor and insulating materials are different. For the conductor, a low electrical resistance is preferred. Most organic PCBs are fabricated with copper conductors which have very low resistance. Ceramic circuit boards, however, may have higher resistance conductors such as silver/palladium or tungsten alloys due to their high temperature processing requirements. For the insulating medium, a low dielectric constant is preferred for lower signal delay and crosstalk. Again, organic PCBs have a lower dielectric constant than ceramic circuit boards. Another important electrical consideration is the dielectric breakdown strength, which is the maximum electric field that can be applied to the materials without causing an abrupt irreversible drop in resistance. This breakdown is often accompanied by the destruction of the material.

Structural requirements of PCB materials are also important considerations in materials selection. The strength provided by the reinforcement is adequate for most commercial applications. In military applications where vibration characteristic is critical, the circuit board is usually bonded onto a metal plate which also acts as a heat sink to draw the heat out of the board by conduction. The resin material does not provide adequate strength to the PCB, but its structural properties are important in manufacturing. Currently, the limitation to fine line technology is not the imaging technology, but the structural properties, such as dimensional stability and warping behavior, of the laminates [15].

One of the most important properties of the resin material which affects its structural properties is its glass transition temperature (Tg). The Tg of an organic material is the temperature below which a polymeric material behaves like a glassy material. Technically, the glass transition phenomenon involves changes in molecular free volume and the relative mobility of individual molecules within the crosslinked lattice [16]. An important consideration of Tg is the weakening of the bond between the copper circuitry and the resin material when the resin is heated above the Tg. This situation is often encountered in the rework process where the PCB must be heated to melt the solder in order to remove the components. If the rework temperature exceeds the Tg of the resin, the pads may be "lifted" with the components, rendering the PCB unrepairable. Moreover, if the resin materials is heated above its Tg during drilling, it becomes easily smeared. Hole smearing interferes with subsequently copper plating processes unless an additional desmearing step is used.

The Tg also affects the coefficient of thermal expansion (CTE) of the PCB. In a PCB, the CTE, both in the plane of the board (x-y CTE) and through the thickness of the board (z-axis CTE), affects the reliability of the board in surface mount applications. The x-y CTE is important in SMT applications because the components are soldered directly onto the PCB. If the CTE of the board and the component are substantially different, the solder joints will be stressed as the components heat up and cool down, leading to solder fatigue and, ultimately, failure of the electrical connection. Z-axis CTE is important because most PCBs contain holes through the thickness of the board which have been plated with copper (PTHs) to provide electrical connections between different layers of the board. If the z-axis CTE of the PCB is substantially different from that of copper, these copper plated connections may fail during thermal cycling.

Another related thermal concern is the thermal conductivity of the PCB materials. Most organic materials are poor thermal conductors. This has forced designers to devise alternate means of thermal management, such as forced convection cooling and immersion cooling, to remove the heat generated by the chips directly, instead of through the PCBs. In some applications, however, operating conditions may limit the use of these cooling methods.

History of PCB Laminate Technology

Figure 4 shows the history of PCB laminate technology, superimposed on the development of IC technology. The first glass reinforced epoxy PCB was introduced in the 1950's. This was soon followed by the fire retardant versions. As IC technology moves into medium scale integration (MSI), the concept of multilayer PCB emerged to accommodate the increased circuit density.

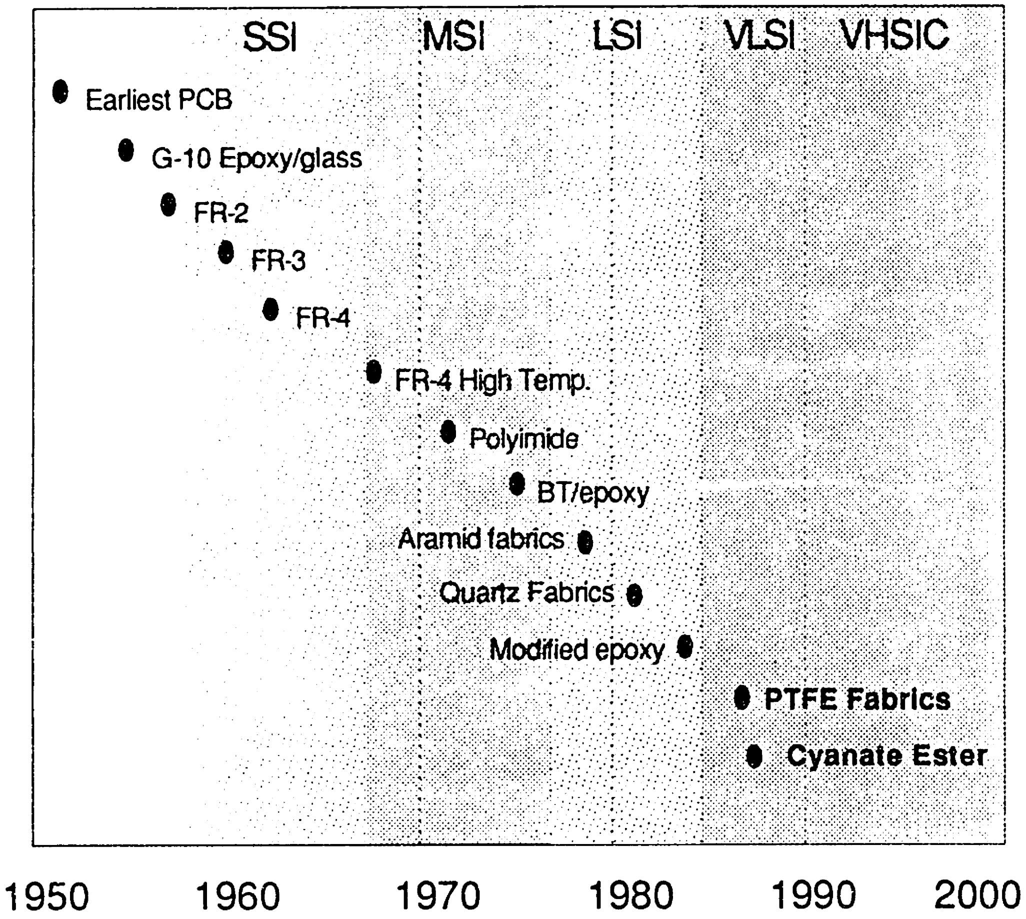


Figure 4: History of PCB Laminates Developments

The increase in complexity and, hence, the value of the board, makes repairability an important consideration in the selection of PCB materials. Hence, reliability and repairability became important, and the existing epoxy systems were modified to improve their high temperature performance. At the same time, polyimide laminate was developed for its superior thermal performance. All these development have led to improved reliability and repairability of PCBs.

As the speed of ICs increased, electrical performance became more important. Subsequently, composite constructions of paper-epoxy core sandwiched between two epoxy-glass plies were used to optimize electrical and manufacturing performance. Bis-maleimide traizine (BT) laminates was introduced as a compromise between lower dielectric constant and higher Tg than epoxy. While improvements were made in the resin materials, developments in fiber technology also resulted in the introduction of new fabrics for PCBs: aramid and quartz fibers for improved electrical performance and a lower CTE for SMT applications. Most recently, PTFE fabrics were introduced for their low dielectric constant [17], and cyanate ester resin was developed to fill the gap between epoxy, polyimide and PTFE by offering a low D.C. of 3.5 and high Tg of 250°C [18].

Table 1 summarizes the properties of the different resin and fiber reinforcement materials used in rigid PCBs today. There are variations within the basic types of laminates available, depending on application and suppliers. In the next few sections, the common types of laminate resins and fiber materials used in the industry and their limitations for SMT applications are discussed.

Table 1: Properties of Resins and Fibers

Resin	Tg(°C)	Dielectric constant	
		Neat Resin	Laminate
Epoxy	125-135	3.5	4.5-5.0
Polyimide	240-280	3.3	4.1-4.7
BT/Epoxy	180-200	3.2	4.0-4.5
PTFE	75	2.0	2.2-2.6
Cyanate Ester	250	2.8	3.3-3.8

Fibers	Density (g/c.c)	D.C. (@1Mhz)	CTE (ppm/°C)
E-glass	2.54	5.8	5.0
S-glass	2.49	4.5	2.9
Quartz	2.2	3.8	0.54
Aramid	1.44	4.1	-2
PTFE	No data	1.7-1.9	No data

Sources:

1. G. A. Bouski, "High Speed Low Dielectric Substrate Materials", *Norplex/Oak Brochure*, June 1, 1988.
2. S. J. Kubisen, P. C. Long,"Electrical Laminates: Where the Industry is Going and Why", *Proceedings of the First Electronic Materials and Processing Congress*, Chicago, Illinois, U.S.A., Sept 24-30, 1988.
3. D. W. Wang, "Advanced Materials for Printed Circuit Boards", *Proceedings of MRS*, Dec 1987, Boston, Massachusetts.

Description of Materials for Printed Circuit Board

Resin Systems:

Epoxy: This class of laminates, commonly appearing as FR-4 resins, was introduced in the 1960's. Chemically, it is a dicyandiamide (dicy) cured brominated epoxy. It can be used in single sided as well as multilayer boards. However, it is used less frequently for high performance computers and military applications because of its low Tg. It also has a higher dielectric constant than some of the newer resins. Its main advantages are low cost, ease of manufacture and compatibility with established manufacturing facilities.

Polyimide: Polyimide offers a higher Tg and a lower dielectric constant than epoxy-glass. However, it is expensive and difficult to process. Because polyimides require higher lamination temperatures, some board shops are not equipped to process them. Other processing operations, such as drilling, also require different processing parameters. The biggest drawback to the widespread use of polyimide is the lack of manufacturing experience in the commercial industry. Another concern, especially in military applications, is that most PCB polyimides are supplied by foreign sources.

Enhanced/Modified Epoxy: Research is being directed at improving the properties of epoxy resin for PCB laminates. From this research, multi-functional epoxies with Tg higher than conventional epoxy are being introduced. These resins show some processing advantages over polyimide resins, but their properties are not as good as that of polyimide.

Bis-maleimide Traizine (BT) Blends: It has been found that blending BT resins with brominated epoxies yields a resin with a higher Tg and a lower dielectric constant. This combination of properties is very attractive to many computer users, especially when it costs less than polyimide. The higher Tg of the BT fraction in the blend improves repairability and dimensional stability, and reduces z-axis expansion, making it suitable for thicker multilayer boards. The dielectric constant of BT/epoxy is lower than that of conventional epoxy, but its adhesive strength to copper is also reduced.

Polytetrafluoroethylene (PTFE): PTFE resin offers the lowest dielectric constant (2.1) in electrical laminates due to its symmetrical molecular structure and minimum dipole. It is used extensively in microwave and high speed applications. PTFE is a thermoset material and has a low Tg of 75°C, resulting in a low modulus, a high CTE and poor dimensional stability. Its main disadvantage is high cost and the requirement of melt-processing lamination temperature of 720°F.

Cyanate Ester: Cyanate ester is a relatively new resin system which attempts to fill a gap in the PCB industry by offering a combination of low dielectric constant (3.5) and high Tg (>200°C). However, its manufacturability and selling price are still speculative at this time. Currently, industrial evaluations indicate that it is compatible with epoxy processing equipment and the resulting boards exhibit good performance characteristics. Thus, at the right price, this material could attract a large market share in high performance commercial applications.

Fibers:

Glass: E-glass is the most commonly used fiber today. The glass fabric comes in different thicknesses and style. Other grades of glass, notably S-glass which has a lower dielectric constant but is more expensive, are also used in higher performance laminates.

Quartz: Quartz fibers offer excellent electrical properties and a very low CTE, which makes them the ideal reinforcements for CTE controlled boards. However, these fibers are very difficult to drill due to its extreme hardness. It is also very expensive and is only available from a single foreign source.

Aramid: Aramid fibers, marketed under the trade name Kelvar, has a high modulus and a negative CTE. This combination of properties makes it an attractive choice in CTE controlled boards [19]. However, the processing problems of aramid reinforced boards, including water absorption and high z-axis expansion, have yet to be overcome.

PTFE: PTFE fibers, marketed under the trade name Gore-Tex, have a low dielectric constant. It has been successfully impregnated with epoxy resin [1]. The main advantage of this laminate is that it offers a lower dielectric constant and can be manufactured with conventional FR-4 processes. However, the price of expanded PTFE fabric laminate is relatively high.

The approximate market share of each type of materials in 1980 and 1985 is tabulated in Table 2.

Table 2: Market Share of PCB Materials in 1980 and 1985

Materials	1980	1985
Epoxy-Glass (FR-4)		
Rigid	65.0%	45.0%
Multilayer	15.0%	40.0%
Paper/Composites	16.0%	8.0%
Polyimide	3.3%	4.5%
BT/Epoxy	0.5%	2.0%
PTFE/Others	0.2%	0.5%
Total	100.0%	100.0%

Applications of Printed Circuit Board

The end user of PCB can be roughly broken down into four categories: commercial, military, consumer electronics and instrumentation. The approximate market share in terms of usage is shown in Table 3 [20]. The commercial industry comprises the computer and telecommunications industry and is currently the largest consumer of PCBs. The military consumes a smaller fraction of all PCBs produced, but it has a great impact on the development of PCB materials and technology because of its stringent materials requirements. Much of the research work on advanced PCB materials is motivated by either the military or the computer industries.

The type of materials used in PCBs depends on their applications. In most applications, the use of epoxy-glass dominates, although the use of lower dielectric constant and higher Tg laminates has increased, especially in the computer and communications industry. The military uses polyimide for most of its more critical applications. Other more expensive materials such as PTFE are also used. Consumer electronics, due to its high cost sensitivity, uses only epoxy-glass and paper composite laminates. The instrumentation industry has very diversified needs, and therefore, it uses a wide range of materials, although epoxy-glass still dominates due to their cost advantage.

With the development of new materials for PCB applications, there arises the question of whether or not they will successfully compete with existing materials and, if not, what must be done to develop materials that will be successful. The evaluation of the potential of new PCB materials is not a simple task, given the diversity of end users, the fragmented nature of the PCB industry, and the number of factors that affect the use of new materials in the industry. Complicating the assessment is the fact that the electronics industry is very fast moving and changes in technology affect material choices. The next section is a review of past market assessment techniques.

Table 3: PCB Consumption by Industry (% of Total)

Industry	1985 Value	1985 %	1990 Value	1990 %
Computers and Communications	$2,662	58%	$6,048	63%
Defense	$826	18%	$1,632	16%
Industrial	$504	11%	$1,152	12%
Consumer	$459	10%	$756	8%
Others	$139	3%	$96	1%
Total	$4,590	100%	$9,684	100%

Source: Printed Circuit Fabrication, Sept 1987.

Past Approach to Market Assessment of Competitive Materials

The PCB market is a $16.4 billion industry worldwide in 1989 [21]. With such a large market, there have been no shortages of market studies on the PCB industry. However, most market studies are focused on the management and financial aspect of the business, examples of such studies are the multi-client consulting reports [22, 23, 24] conducted by various consulting companies. Since the materials market is only a small part of the total PCB market, market studies focusing on the materials and their competition has been limited. To date, three basic techniques have been used to assess the prospect of new materials in this market:

1. Opinion Survey
2. Historical Data Analysis
3. Cost Analysis

Opinion Survey

The opinion survey is a convenient way to assess an industry's material needs. In this approach, a survey is sent out to prospective and current materials users and the data is collected and tabulated. The survey may either focus on the performance levels of current materials such as Tg and dielectric constant, or it may use performance measures as the basis for discussions, such as "What are the limitations of today's laminates?". The results may be used to discuss qualitatively the potential of new materials or to direct attention to the performance improvements required from new materials [25].

Although opinion survey addresses the issue of performance by assessing the degree to which current materials satisfy the needs of the industry, the analysis cannot be extended to speculate on new materials and perform sensitivity analysis to predict the competitiveness of new materials if certain performance characteristics can be improved. Cost is also not explicitly included, nor are the processing requirements of new PCB materials.

Historical Data Analysis

This approach uses historical data to project the growth of materials in the industry. Several trade organizations, most notably the Institute of Printed Circuits (IPC), have been collecting data on the use of PCB laminates for many years. The data can be used to investigate the trends of the industry. Typically, a growth rate is cited for each material for the next period, and the sum of all the materials demanded, as estimated using the growth rate, yield the projected industry consumption. This growth rate is assessed qualitatively based on economic outlook and historical trends, and through discussion with experts in the industry. For example, one consultant estimated that PTFE will grow at 15.5% over the next few years based on his assessment of market needs and historical data [26].

The use of historical data works well with "mature" materials in the industry, but it becomes highly subjective when it is applied to new materials because experts' opinions may differ tremendously [27]. Furthermore, this technique lacks the sophistication required to perform sensitivity analysis to investigate the effects of changing certain performance characteristics of new materials on their overall attractiveness. This insight is extremely crucial for new materials development efforts.

Cost Analysis

Cost analysis is not a market assessment technique *per se*, but it is not uncommon for manufacturers and suppliers to discuss the prospect of new materials based solely on its raw material cost [28]. This is consistent with many designers' requirements that new materials must at least be compatible with existing manufacturing practice and offer either improved performance or lower cost. PCB manufacturing is a relatively complex multi-step process, and it is very difficult to estimate the cost of a PCB before actual production. One approach is to estimate the cost based on historical data according to some attributes of the PCB, such as the number of layers and the circuit density of the boards. This approach works well with existing materials, but breaks down when the cost of PCB fabricated from new materials must be estimated. New materials may require different processing parameters or the resultant yield may be so different from existing materials that any estimate based on current cost data is at best a guess.

From the shortcomings of these three techniques, it is obvious that an objective market assessment of the potential of new materials in this market requires more than just a prediction of future growth, a simple cost analysis or a survey; it should include an assessment of the dominant technology in the industry, the manufacturing capabilities of the industry, the compatibility of new materials with the existing manufacturing facilities, the economies of using new materials, and most important, the "real" requirements of the new materials in terms of its expected final performance. Therefore, the objective of this research is to develop a technique to carry out the market assessments of new materials which addresses these issues.

Summary

Packaging and interconnection technologies have emerged as one of the critical limitations to continuous improvement in the performance speed and size of electronic devices. The conventional method of packaging single chip in packages and mounting them onto printed circuit board (PCB) will prevail over the next few years because it is a mature technology compared to the newer interconnection technologies. Surface mount technology has led to improved performance of the single chip packages. The next important improvement must come from PCB technology through the development of better materials, design and manufacturing technology.

New PCB materials will play a major role in achieving the goal of improved performance, and therefore, an understanding of the needs of the PCB industry and the prospect of new materials is crucial. Current techniques used to evaluate the potential of new materials are opinion survey, historical data analysis and cost analysis. Each technique addresses a different aspect of the materials selection problem but does not approach the problem in its entirety. Thus, the objective of this study is to develop a better technique to analyze the market potential of new materials in the PCB industry. The methodology is described in the next chapter.

METHODOLOGY

An objective market assessment of the potential of new materials is a major task because many issues have to be addressed simultaneously. To simplify the task, the material selection problem is addressed first. In a perfect market, the most desirable materials will be used, and therefore, it will have the greatest market potential. In the presence of market imperfections, however, the most desirable materials may not be used due to factors such as the cost of switching over to a new material and learning curve effects. Therefore, this study will first characterize the material selection process for PCBs using multi-attribute utility analysis (MAUA). Cost issues will be incorporated into the study by using technical cost modeling. After the material selection problem is resolved, the potential demand for new materials is assessed using demand analysis to account for market imperfections. In this way, relevant market issues can be addressed without complicating the problem excessively.

The methodology consists of the following five stages:

1. Identify Application and Material Alternatives
   First, viable designs and prospective materials for a specific application are identified through a literature search, surveys, and interviews with people in the industry. Although the selection of a specific application may limit the scope of the study, it provides a better understanding of materials requirements, rather than trying to assess the general requirements of the whole industry. The scope covered depends on the specific case study; if necessary, design variations can be included.

2. Quantify Performance of Alternatives versus the Requirements of the Application.
   At this stage, the performance of each alternative is quantified using engineering and systems analysis. The important performance characteristics of the system are determined for the application. Since cost is usually an important factor in materials selection, a technical cost model capable of simulating the cost of fabricating PCBs is developed. Technical cost modeling differs from conventional cost analysis in that it is developed based on manufacturing processes, rather than

historical cost data. However, historical cost data is used to verify the cost estimates generated from the technical cost models. The cost model will consider the viable designs and the prospective materials, including materials at the developmental stage. Competing manufacturing technologies are included in the cost model to evaluate their impact on materials. The development of such a model allows the analyst to address many issues that the conventional cost analysis could not, such as investigating the effects of new materials and technology on yield and cost. The methodology used for cost estimation is discussed in the next chapter.

3. Characterize the current material selection process in the PCB industry.
   The procedure for material selection in the industry is documented and analyzed. In the case of a new material offering improvement in one performance characteristic with a cost penalty, such as lower dielectric constant but higher cost, there is no inherent engineering or economic relationship that dictates the "best" solution; the final decision is made based on how much value the engineer places on dielectric constant and cost. In some applications, the lower cost alternative may be preferred and vice versa. Thus, materials selection decisions are made according to the value placed on different performance characteristics.

   One technique to evaluate the value placed on different performance characteristics is multi-attribute utility analysis (MAUA). MAUA has been applied to material selection in the automobile industry [29, 30]; its applicability to the PCB industry is investigated in this study. Interviews with engineers directly involved in selecting materials for PCBs are undertaken to understand the engineers' preference. From these results, the utility of the various materials-design combinations can be quantified and new materials can be evaluated based on the performance they offer to the engineer. A description of MAUA is given in Chapter 4.

   The use of MAUA enables the analyst to focus on application requirements rather than specific materials. It provides a yardstick for evaluating materials against the required performance. This feature is very important because a PCB is a composite material and its properties can be tailored by using different raw materials or different processing parameters. MAUA is different from opinion survey in that it focuses on the preference of the engineer based on his needs, rather than performance levels of current materials. The results from MAUA can be used to perform sensitivity analysis to investigate the effects of changing one performance characteristic of a material, such as the Tg, on the overall desirability of the material. In this way, the prospects of new materials can be evaluated.

4. Analyze alternatives/new materials and suggest strategies for development.
   Using the results from MAUA, the performance of viable designs and material combinations are evaluated. A ranking of materials is made and sensitivity analysis can be performed. If new materials appear to be uncompetitive, MAUA can provide information on the required performance or price improvement to make the material competitive. In this regard, MAUA can be used to direct materials research efforts. In approaching market assessment by analyzing material selection in the industry, issues in material performance, design, manufacturing and economics can be simultaneously addressed.

5. Demand Analysis
   At this stage, the most desirable material alternative for the specific application, based on the preference of the engineer, becomes obvious. However, the demand for this material is still highly uncertain because of market imperfections. This is especially true if the most desirable material differs from current established materials. To estimate the demand for new materials, market imperfections and purchase dynamics must be considered. This is accomplished by using a demand model derived from markov chain. The model is based on material switching and substitution. Utility measures of the materials are included in the analysis using the framework of logit analysis. Other factors such as inertia of the industry, compatibility of materials with existing manufacturing capabilities and design cycles can be included in the estimation of demand. The derivation of the demand model is given in Chapter 5.

Two case studies, one selected from the commercial industry, and one from the military industry, are used to illustrate the use of this five-step methodology to PCB materials. The commercial industry was selected for analysis due to its large PCB consumption and, hence, its influence of the direction of the PCB industry. On the other hand, an analysis of the military industry provides the opportunity to investigate the "leading edge" technology in new PCB materials developments. There is a potential for eventual commercialization of new materials from military research when the materials are better characterized and their cost is lower.

Summary

The unique feature of this five-stage assessment technique is that it combines the performance requirements with economic consideration through the use of MAUA and technical cost modeling. Technical cost modeling is superior to standard cost analysis because it is based on engineering and manufacturing information. MAUA yields a quantitative, materials blind measure of the relative value placed on material performance. This allows the comparison of specific alternatives, as well as the identification of the extent the performance of a particular alternative must change in order to be competitive. After the material selection decision is analyzed, the demand for new materials is assessed using a demand model founded on utility measure and material switching behavior.

TECHNICAL COST MODELING

Introduction

Materials choices are affected by manufacturing technologies. In some cases, advances in manufacturing technology may render new materials competitive. In most cases, however, the manufacturing requirements of the new materials must be compatible with existing industry practice. In PCB manufacturing, the manufacturing processes, and hence the economics, are different for different materials. Furthermore, as PCB becomes more complex and specialized, understanding the cost of fabricating PCB as a result of design becomes more important. However, the common industrial approach of using an aggregated cost for the assessment of new materials is inadequate; it does not take into consideration the specifics of the particular PCB and its degree of manufacturing difficulties. Hence, there is a need for cost estimates based on manufacturing requirements, rather than historical cost data. This can be accomplished through technical cost modeling.

Technical cost modeling is an extension of engineering process modeling with particular emphasis on capturing the cost implications of process variables and economics parameters. By grounding the cost estimates in engineering knowledge, critical assumptions, such as processing rates and materials consumption, interact in a consistent manner to provide an accurate framework for economic analysis. Technical cost modeling can be an extremely useful tool to:

1. Explore the cost effects of competitive materials and processes
2. Guide price quotation based on manufacturing difficulties
3. Evaluate alternative manufacturing processes, such as whether to use automatic or manual inspection, without expensive expenditure of capital and time.

Technical cost modeling approaches cost estimation by estimating the individual elements that contribute to total cost. These individual estimates are derived from basic engineering principles, from the physics of manufacturing process, and from clearly defined and verifiable economic assumptions. Technical cost modeling essentially reduces the complex problem of cost analysis to a series of simpler estimating problems, and brings engineering expertise, rather than intuition, to bear on solving these problems.

Review of Manufacturing Technologies for PCB

The simplest type of PCB is the single sided PCB which, as the name implies, has circuitry on only one side of the board. The circuitry may be formed by an additive or subtractive process. In the additive process, the copper circuitry is "added" onto the surface of an unclad board using a chemical process. In the subtractive process, the starting material is a copper clad laminate and the excess copper is later etched away to from the circuitry. Due to the different processing requirements for the additive and subtractive process, the material requirements and economics are different.

Applications of single-sided boards are limited because they can only accommadate a small number of circuit lines per unit area, even when thin lines are used. One way to increase the circuit density is to put circuitry on both sides of the board. To provide for interconnection between the top and bottom layer of the board, holes are drilled through the board and then plated with copper. Figure 5 and 6 show the typical manufacturing sequence for double-sided board with additive and subtractive process, respectively. Variations on these two basic processes are possible. For example, the partially-additive process uses a thin copper clad laminate. After the resists are printed, the excess copper is etched off. Copper is then added onto the circuit lines to produced the final circuitry. Detailed descriptions of these processes can be found in Reference [31].

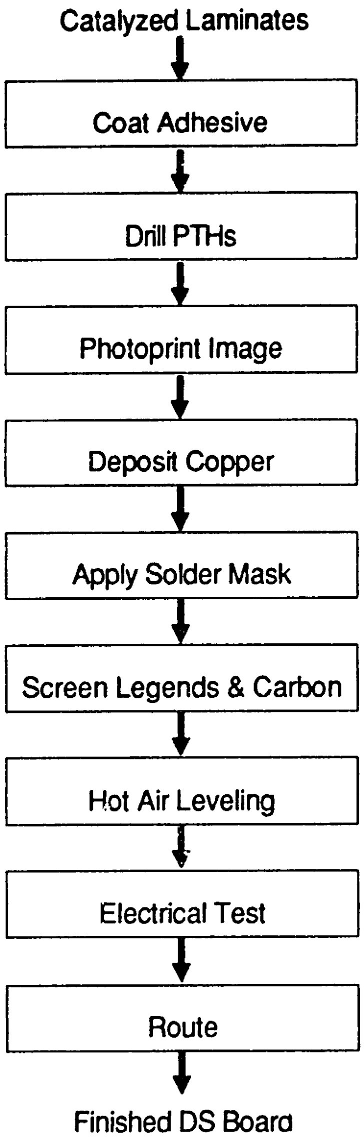


Figure 5: Flowchart of Additive PCB Manufacturing

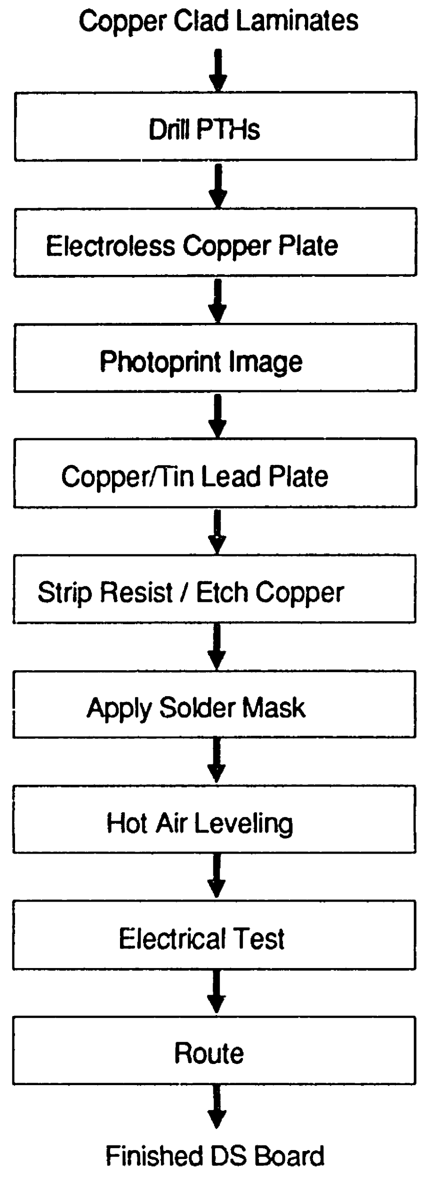


Figure 6: Flowchart of Subtractive PCB Manufacturing

As IC increased in complexity, the amount of interconnection required on the PCB increased too. Soon, the available circuit density on a double sided board exceeded the required circuit density. One way to increase the circuit density is to use very fine circuit lines. This, however, increases the crosstalk and reduces the manufacturing yield. Another method to increase circuit density without reducing the line width is to increase the number of circuit (or signal) layers, known as multilayer technology.

There are two ways to build multilayer boards: parallel and sequential. The parallel approach is an extension of basic double sided manufacturing, where numerous thin double sided board are made, stacked together, and laminated at high temperature and pressure. The innerlayers may be fabricated using the additive or subtractive process. The laminated stack is then drilled and copper plated to provide interconnection between the layers. A typical multilayer processing is shown in Figure 7 and 8.

The sequential multilayer process is used with the additive process. After the first two layers are processed, a layer of dielectric material is screened onto the panel. A third layer of circuitry is the "added" on. This process is continued until the desired number of layers is reached. Normally, the number of layers built with this method does not exceed six. Figure 9 shows a typical sequential manufacturing process for a multilayer board.

Most PCBs are produced by the subtractive process in the US. In Japan, however, the use of additive process prevails [32]. In the past, the quality of the electroless plated copper was inferior to the copper foils used in the subtractive process. As a result, the additive process is used mainly in consumer products. This situation has been changed through process development; high quality copper can now be produced with the additive process [33]. This improvement should enable the additive process to compete with the subtractive process.

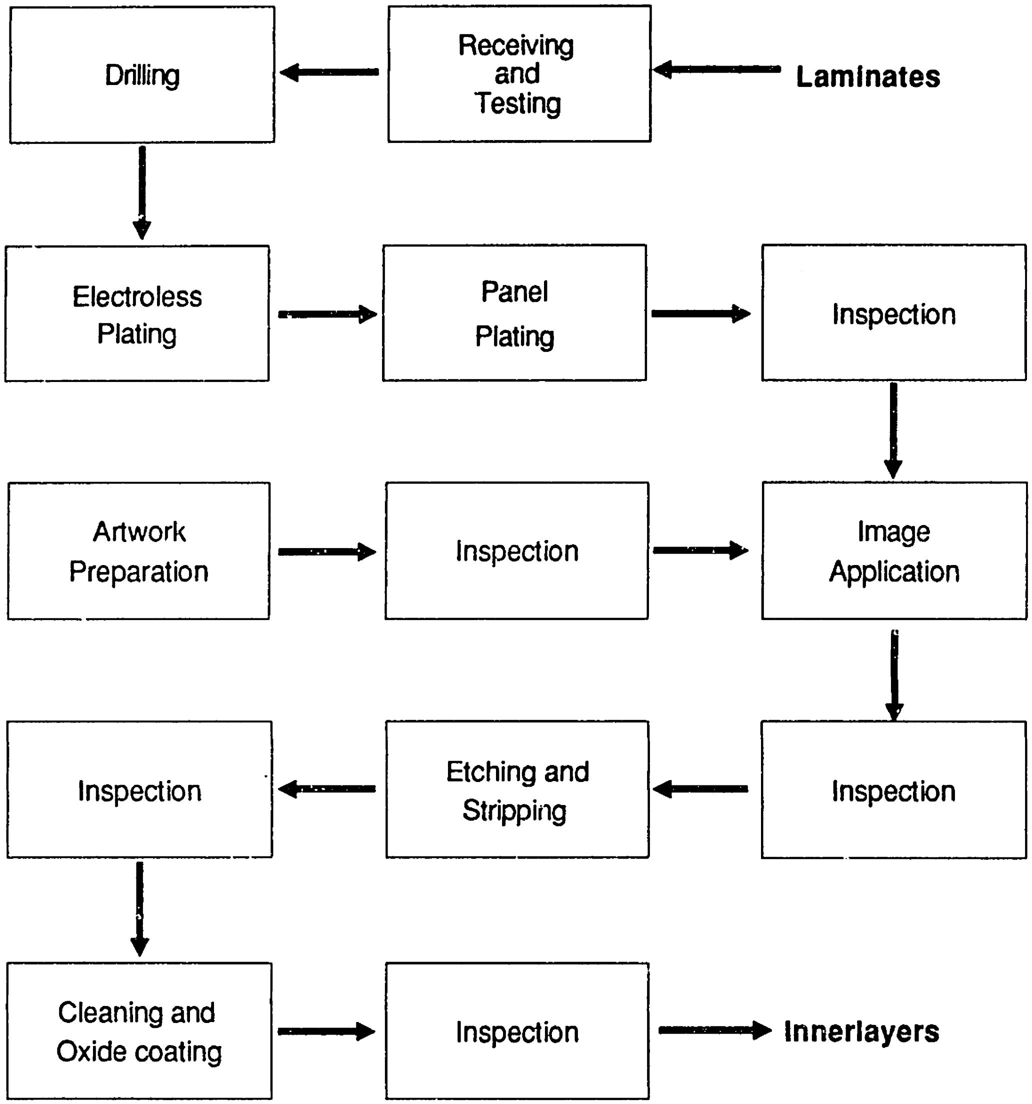


Figure 7: Flowchart of Innerlayers Production for multilayer PCB

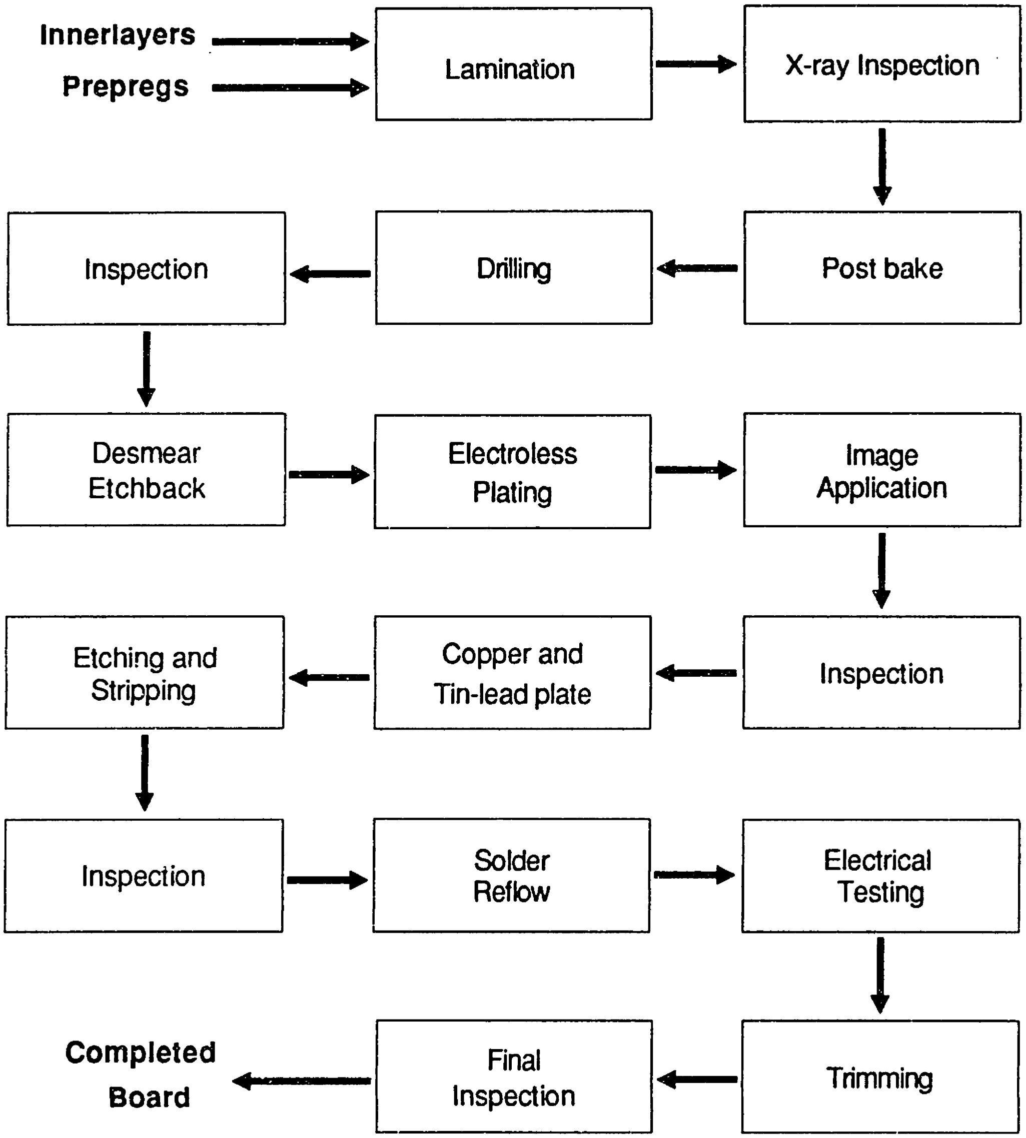


Figure 8: Flowchart of Panel Production for Multilayer PCB

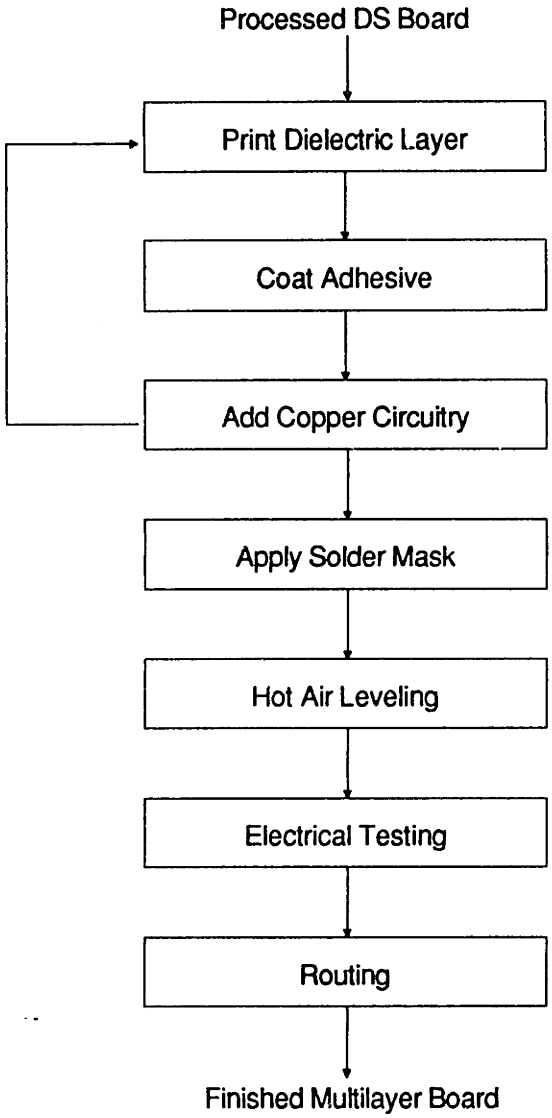


Figure 9: Flowchart for Manufacturing Sequential Multilayer PCB

The advantages of the additive process are less processing steps, and the ability to produce finer lines. The ability of additive process to produce boards with finer lines than the subtractive process is due to the elimination of etching stech which etches the copper away to form the circuitry. Chemical etching produces circuit lines with a cross section that look like mushrooms, rather than being rectangular. This is commonly known as the undercut problem, which degrades electrical performance. The main advantage of subtractive process is that it is very established. Obviously, there are advantages and disadvantage associated with the additive and subtractive process. The choice of the process depends not only on the physical characteristics of the PCB, but also the economics of the manufacturing process. The latter issue will be explored in this chapter using the PCB cost model.

PCB Cost Model

In developing the cost model, the existence of a board shop capable of producing the specified number of boards per batch is assumed. However, no assumption is made regarding the overall size of the operations, except that the board shop operates at a certain level of automation. In this regard, the cost model is an *a priori* model which allows cost estimation before the product is actually made; it does not attempt to model any existing facility, although it can be readily modified to do so when necessary. As a result, delivery schedules and overtime requirements are not included in the cost model.

The cost model was developed on a Lotus 123 spreadsheet. Two models were developed for the double sided board: one using the additive process shown in Figure 5, and one using the subtractive process shown in Figure 6. The additive double sided PCB cost model can be used to estimate the cost of mass laminated multilayer boards. These boards have innerlayer circuitry developed at the suppliers site; only the external layers are processed by the board manufacturers. A multilayer model for both buried vias and plated through holes (PTHs) using parallel subtractive process was also developed according to the process sequence shown in Figure 7 and Figure 8.

The development of the PCB cost model is very tedious because the fabrication of PCB involves multi-step processes, analogous to assembly operations. PCB manufacturing also involves wet processing with resultant chemical waste disposal and treatment cost implications. This necessitates detailed modeling of the chemical bath, rate of chemical consumption, and the kinetics of the process. Thus, a large amount of information must be collected and organized in a consistent framework within the cost model. At the same time, the effects of board attributes on the yield of the processes must also be modeled, as well as the operating conditions for each type of material. This was accomplished through an extensive literature search and discussion with equipment suppliers and board manufacturers. The resultant cost model is quite large because of the incorporated information. The PCB cost model and its cost estimation algorithm have been discussed in reference [34]. The next few paragraphs summarize the cost estimation procedure.

To start the cost calculation, a description of the board whose cost is to be estimated must be supplied, together with other economic and plant operation assumptions. An expected yield can also be input; otherwise, a default value will be used. Next, the processes required for the production of the input board can be selected. If no process selection is input, the cost model will use a set of default processes according to the attributes of the board. Table 4 shows the required board description and economic assumptions input of the cost model, while Table 5 and 6 shows the required inputs for process selection.

The cost calculations are greatly simplified by breaking the total cost into six individual cost elements: product materials, process materials, machine, tooling, labor and overhead cost. Each cost element is calculated separately for each unit process.

Table 4: Inputs To the Multilayer Cost Model

BOARD DESCRIPTION			
Size of Board	5.25	by	6.00 in
Area of Board	31.5	sq in	
Thickness of Board	101	mils	
No of layer/board	12	layers	
Line width/spacing	6	mils	
No of PTH/board	1200	holes	
Diameter of PTHs	2	mils	
Buried vias/2 layer	0	holes	
Diameter of Buried Vias	0	mils	
Pairs of Via Layers	0		
Lot size	100	boards	
Panel dimension (inches)	12	by	18
No of boards/panel	2		
Test points/board	1200	points	
MATERIALS USED:	**No**	**Menu**	**Description**
Laminates	6	1	Epoxy-glass
Prepreg Construction			
Style 2116	2	1	Epoxy-glass
LABOR RATES	**$/shift**	**hrs/shift**	**days/yr**
Manual	21	8	240
Semi-skilled	35	8	240
ELECTRICITY			
Cost of Electricity (KWh)	$0.08		
Power Efficiency	80%		
ACCOUNTING ASSUMPTIONS			
Cost of capital	15%		
Life of equipment	5	years	

Table 5: Process Inputs For Innerlayer To the Cost Model

PROCESS PARAMETERS AND SELECTION

		Yield	Hours	labor	Machine
				Productivity	
INNERLAYERS					
Inspection	1	96%	24	75%	75%
Clean and Oxide Coat	1	100%	24	80%	80%
Inspection	1	95%	24	80%	80%
Stripping and Etching	1	100%	24	90%	80%
Inspection	1	95%	24	80%	80%
Image Application	1	100%	24	80%	80%
Artwork Preparation	1	95%	8	80%	80%
Panel Plate	0	99%	24	90%	80%
Electroless Plate	0	100%	24	90%	80%
Drilling	0	100%	24	90%	80%
Receiving & Testing	0	100%	8	75%	80%
Innerlayers production	------------------------>> 469				
Calculated Yield	------------------------>> 87%				
Assumed Yield	------------------------>> 85%				

Table 6: Process Inputs For Panel To the Cost Model

PROCESS PARAMETERS AND SELECTION

		Yield	Hours	labor	Machine
				Productivity	
PANELS		Yes = 1		No = 0	
Final Inspection	1	98%	24	70%	75%
Trimming	1	100%	24	80%	80%
Solder Mask	1	99%	24	80%	80%
Dry Film	0				
Electrical Testing	1	100%	24	90%	80%
Solder Reflow	1	100%	24	80%	80%
Inspection	1	100%	24	80%	80%
Stripping and Etching	1	100%	24	80%	80%
Tin lead Plate	1	100%	24	80%	80%
Copper Plate	1	95%	24	80%	80%
Inspection	1	95%	24	80%	80%
Image application	1	100%	24	80%	80%
Electroless Plating	1	100%	24	90%	80%
Etchback (0.5 mils)	1	100%	24	80%	80%
Desmear	1	100%	24	80%	80%
Plasma	0				
Inspection	1	95%	24	80%	80%
Drilling	1	100%	24	80%	80%
X-ray Inspection	1	84%	24	80%	80%
Post Bake	1	100%	24	90%	80%
Lamination	1	100%	24	90%	80%
Vacuum	1	100%	24	90%	80%
Panel production	------------------------>> 61				
Calculated Yield	------------------------>> 71%				
Assumed Yield	------------------------>> 85%				

The sum of all the cost elements for all the unit processes yields the final cost estimate. The cost of artwork generation and working diazos may be included in the cost estimate.

Product materials are raw materials used to fabricate the part. In this case, product material cost are calculated from the cost of the laminates used in the panel and the yield of the process. Process materials are calculated from the requirements of the process. The cost of dry film is calculated from the area of the panel, while chemical consumption is calculated based on the capacity of the chemical bath and process requirements. Since there is a cost associated with filling up the bath with chemicals, a rent is charged for the use of chemicals. In some cases, the chemicals are physically consumed and have to be replenished. These costs are also included in the process cost calculations.

To calculate the machine cost, the total machine cost must be distributed to the parts produced over the life of the equipment. The simplest method is to distribute the cost by dividing the annualized investment cost of the equipment by the annual production volume. This assumption is most applicable to situations which call for dedicated equipment. In PCB production, however, this assumption is inappropriate because most board shops produce "batch job". Thus, it is more appropriate to use a non-dedicated assumption that charges a rent for the use of the machine for each batch. To calculate the machine rent, the amount of annual payment needed to pay off the total machine cost at a certain interest rate over the life of the machine is divided by the total productive hours in a year to yield an hourly rent. The total cost of using the machine can be calculated from the machine rent, machine productivity, and the total time required to produce a part.

The cost contribution of tooling is difficult to estimate for two reasons. First, it is difficult to estimate the cost of a set of tools accurately. The cost depends on many factors such as the design and size of the part, the level of automation, the material of construction and the quality of the tool and often vary widely, depending upon the suppliers. Second, it is difficult to estimate the productive life of the tool. Tool life is also a function of the design of the tool, the material, the production volume and the maintenance procedures. Because tools wear out, the cost model must estimate the total number of tools required to produce the batch of job.

Labor costs are calculated from the total machine time, the labor requirement of the equipment and the wages paid, including labor overhead for medical and retirement benefits. In some cases, the labor requirement may be fractional when one man can operate more than one automated machine. There is an inherent a trade-off between the required labor and the level of automation. For example, in the scrubbing step, an autoloader is used, but it can be replaced with an additional laborer at the machine. The cost of energy is calculated from the power rating of the equipment, the total machine hours required for the job and the cost of electricity.

In addition to these costs, there are also costs associated with operating the plant which cannot be attributed to a single process step or product. Among these are the cost of supervisors and engineers, administration, waste disposal, building, machine installation and maintenance. These costs are all lumped under fixed or variable overhead cost. Fixed and variable overhead are calculated as a fraction of total machine and labor cost respectively. The cost of waste disposal is estimated to be a fraction of the process material cost.

A summary of all the formulae used in the cost model is given in Table 7. After all the cost elements are calculated for each unit process, the cost per board is calculated by dividing the total cost by the total number of boards. A typical output from the cost model is given in Table 8 and 9. A cost summary with the individual cost element itemized under product and process material, machine, tooling, labor, energy and overhead is given, together with a breakdown of each individual processing step.

Table 7: Formulae Used in the Cost Model

Raw Materials

$/Board = $/sf * sf/Board / Yield

Equipment

Dedicated - Plant dedicated to annual production of N boards

$/board = Annual Equipment Cost / Annual Production

Non-Dedicated - Batch Job Production

$/board = $/Machine hour * Cycle time / Yield

Labor

$/Board = $/hr * Cycle time /Yield

Energy

$/Board = $/kWh * Machine kW * Cycle Time / Yield

Overhead

Fixed Overhead = Percentage of Equipment Cost

Variable Overhead = Percentage of Labor and Energy Cost

Waste Disposal Cost = % of Process Material Cost

Table 8: Output From Multilayer Cost Model

COST SUMMARY FOR PCB	Total	$/board	Percentage
Product Material	$1,804	$18.04	12%
Process Material	$1,586	$15.86	10%
Capital	$2,300	$23.00	15%
Tooling	$653	$6.53	4%
Labor	$4,560	$45.60	30%
Energy	$1,099	$10.99	7%
Overhead	$3,257	$32.57	21%
Total	$15,260	$152.60	100%
Value Added	$149.61		
$/sq. in	$4.84		

Table 9: Process Breakdown Cost From Multilayer Cost Model

PROCESS COST SUMMARY

Laminates	$1,383	Prepregs	$421
Raw Materials	$1,804		

INNERLAYERS	Total	Capital	Mat'l	Labor	Tool	O'head	Elect
Receiving	0	0	0	0	0	0	0
Drilling	0	0	0	0	0	0	0
E'less Plate	0	0	0	0	0	0	0
Panel Plate	0	0	0	0	0	0	0
Artwork	431	181	61	47	0	140	1
Image App	1540	216	477	403	0	352	92
Inspection	201	1	0	153	0	47	0
Etch & Strip	2267	339	26	1168	0	573	161
Inspection	328	137	0	146	0	44	1
Oxide Coat	985	38	325	307	0	282	33
Inspection	188	1	0	143	0	44	0
TOTAL	5941	914	889	2367	0	1482	289
PANELS							
Lamination	3462	887	37	624	353	848	712
Post Bake	70	7	0	42	0	17	4
X-ray Inspect	213	8	0	154	0	50	1
Drilling	295	52	47	78	60	55	3
Inspection	272	85	0	109	0	76	3
Etchback	388	15	110	165	0	83	16
E'less Plate	274	18	122	45	0	85	4
Image app.	382	45	134	109	0	74	20
Inspection	66	23	0	24	0	0	1
Plating	234	42	44	59	0	81	8
Etch & Strip	777	61	95	412	0	181	28
Inspection	70	24	0	26	0	20	1
Solder Reflow	100	10	16	38	0	27	8
Electric Test	299	15	0	28	240	16	0
Solder Mask	451	56	92	154	0	106	0
Trimming	151	39	0	73	0	38	1
Final Inspect	72	1	0	55	0	17	0
TOTAL	15323	2300	1586	4560	653	3257	1099
PERCENTAGE	100%	15%	10%	30%	4%	21%	7%

All numbers are in dollars

Results of PCB Cost Model

In order to verify the validity of the cost model, a 12 layer SEM "E" PCB was selected for detailed cost analysis. The result of the cost analysis is later used in the military case study. The hypothetical PCB described by Table 4 is used as the basis for cost estimation. Table 10 lists the raw material cost of laminates and prepregs and the assumed yield used in the cost model. It also lists the processing parameters used for different materials. Based on the board specification and a production volume of 100 boards, the cost of producing the 12 layer board using epoxy-glass, epoxy-kevlar, polyimide-glass and polyimide-quartz is estimated using an 85% yield on a 2 boards per panel configuration. The estimated cost for the different materials is given in Table 11, broken down into raw material and its five major processing steps: inspection, drill and plate, lamination, etching and others.

The cost of a 12-layer 5.25" by 6" epoxy-glass board is estimated to be $153 with raw material making up only 12% of the total cost. For polyimide, the board cost rises to $251. With quartz reinforcement, the estimated board cost is $620 with 62% of total cost in raw material. Finally, when epoxy reinforced with 108 glass style kevlar is used, the raw material cost is an overwhelming 81% of the total cost of $817 for the board. The graph also shows that the estimated cost of some processing operations is different for different materials. For example, because polyimide-quartz is harder to drill than epoxy-glass, the estimated cost of drilling is higher in the polyimide-quartz case. The estimated cost breakdown indicated that raw material may not be a substantial percentage of total cost; thus, using the raw material cost for materials selection can be very misleading. Only when epoxy-108 glass style kevlar or similar expensive materials is used does the cost of raw material become the major cost contributor.

Table 10: Assumptions Used in the Cost Model

Materials	EG	PG	PQ	EK(120)	EK(108)
Raw Material Cost ($/sq.ft.):					
Laminates	$2.52	$8.00	$34.16	$15.29	$70.00
Prepregs	$0.46	$2.12	$21.68	$10.05	$15.00
Processing Parameters:					
Oxide	black	red	red	red	red
Lamination					
Temperature (°F)	360	425	425	380	380
Press time (min)	90	210	210	120	120
Post bake (min)	180	240	240	0	0
Panel/Stack	1	1	1	1	1
Drill life (holes)	2000	500	50	250	250
Resharpen (times)	3	1	1	1	1
Mill life (ft)	500	200	100	200	200

Table 11: Estimated Cost of SEM "E' PCBs

Process	EG	PG	PQ	EK(120)	EK(108)
Laminates	12%	25%	62%	53%	81%
Drilling	8%	7%	10%	7%	3%
Imaging	32%	21%	8%	15%	6%
Lamination	23%	31%	12%	13%	5%
Inspection	11%	7%	3%	5%	2%
Others	14%	9%	5%	7%	3%
Total %	100%	100%	100%	100%	100%
Total Cost	$153	$251	$620	$334	$817

It is instructive to investigate the sensitivity of model results to various and environmental parameters. One of the most important parameters affecting the estimated cost is the assumed compounded yield of the PCB manufacturing process. Figure 10 shows that the per board cost of a kevlar based board is more sensitive to yield than that of epoxy-glass board. This is because of the high raw material cost. If the yield for manufacturing epoxy-kevlar (108 glass style) PCBs were increased to 90%, the cost would be reduced to $800. For the epoxy-glass board, the reduction in cost through improved yield is much less significant.

Another factor that affects cost is the number of boards per panel. In PCB manufacturing, the production rate is determined by the panel being processed. Therefore, the more boards per panel, the lower the per board cost. However, the more boards per panel, the lower the yield due to the difficulty of innerlayers registration. Thus, it is customary for a manufacturer to use a "1 up" design (1 board per panel) to maximize yield. As Figure 11 indicates, it may be possible to reduce the total cost of the board by switching to a "2 up" design even though the yield may be lower. The curves in the graphs result from the assumptions used in the model and therefore should not be taken as absolute result. Rather, this example illustrates the capability of the cost model as a tool to investigate the effects of design or manufacturing changes on the cost of fabricating PCB.

The cost model can also be used to estimate the cost of using less commonly used materials such as Rogers Corporation's RO-2800, cyanate ester (Norplex/Oak, Nelco) and Gore-Tex (Gore) laminates. Actual processing parameters for these materials are not available, but they can be estimated from published data and discussions with manufacturers. While these parameters represent only best engineering judgments, the cost model can be used to evaluate the cost consequences of these estimates. In this way, preliminary estimates can be readily generated in advance of hard engineering data.

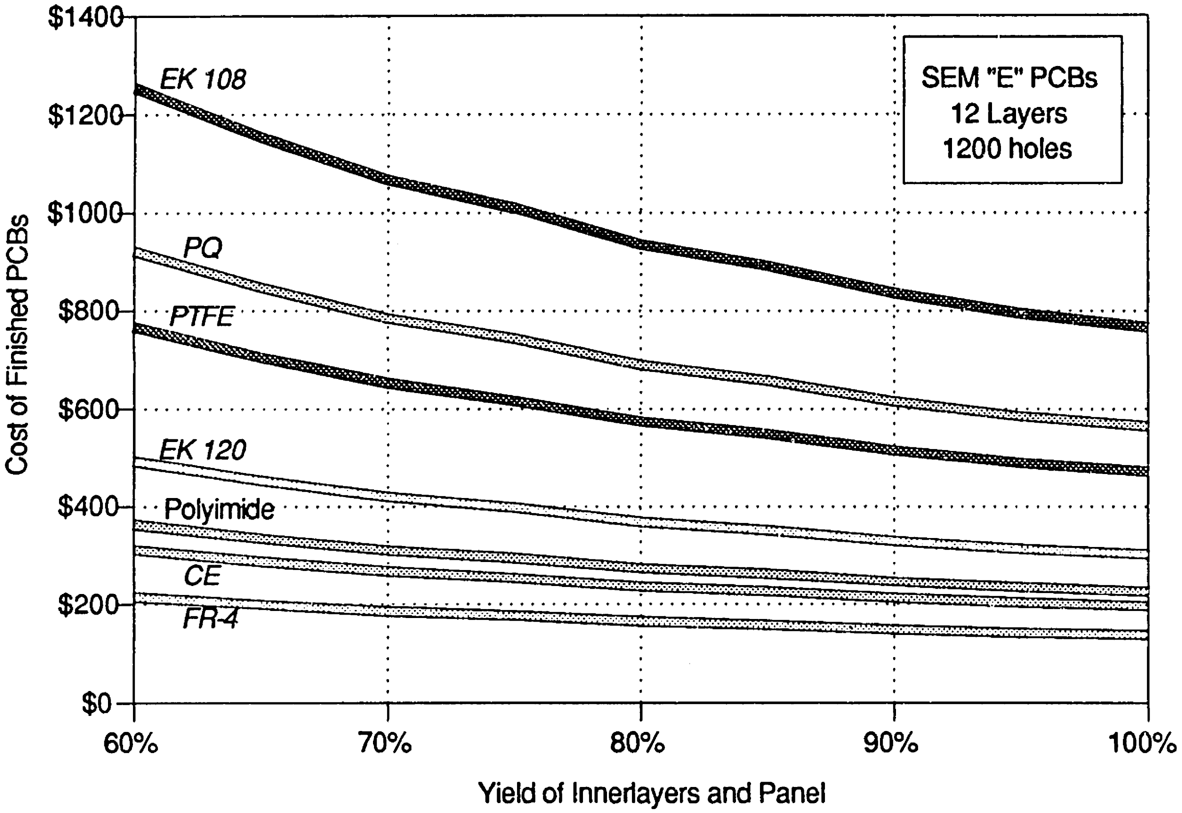


Figure 10: Sensitivity of Cost to Yield

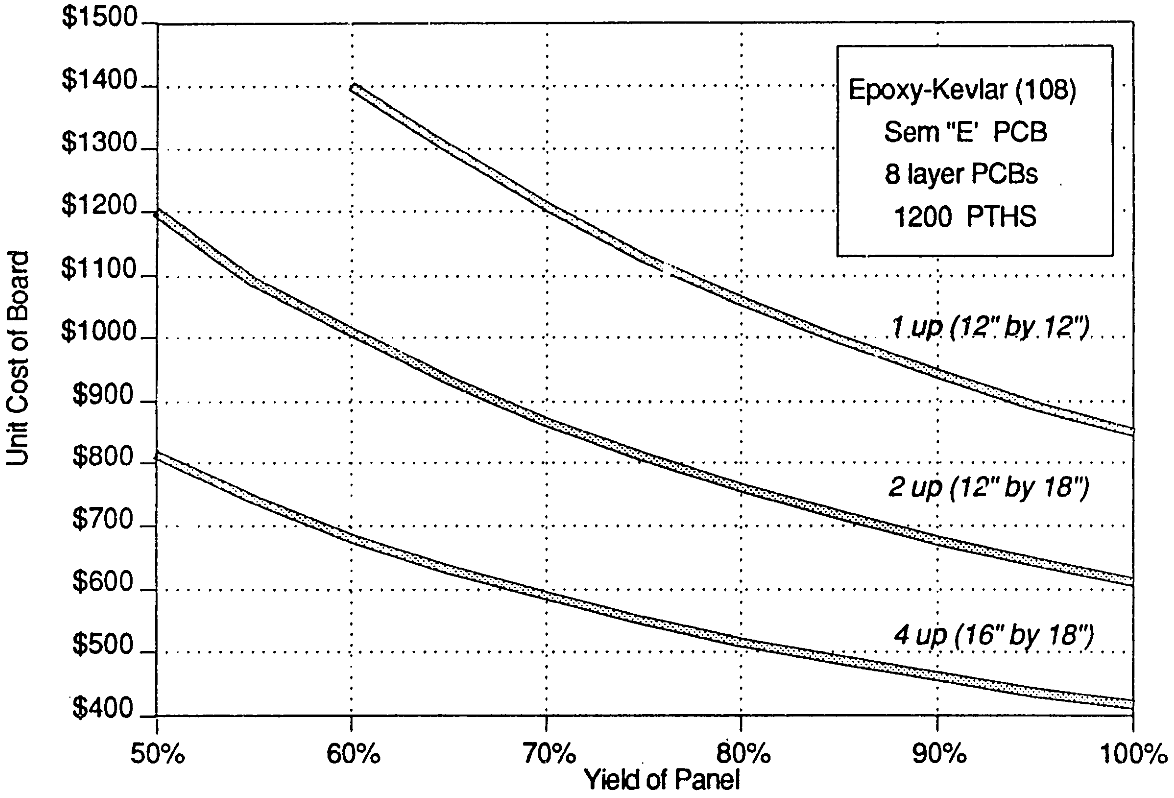


Figure 11: Sensitivity of Cost to Panel Layup

Other Applications of PCB Cost Models

Although the cost model was developed to estimated the cost of PCB for materials selection decision, it can be used as a decision tool to evaluate alternative manufacturing processes and technologies, and to direct R&D. In many manufacturing operations, there are alternative processes, as well as technologies, available to fabricate the part; PCB manufacturing is no exception. The choice of manufacturing processes depends on many factors, such as line tolerance, hole sizes, production volume and the economics of the various processes. The cost modeling approach described earlier can be used to capture the cost implications of using different processes

This section illustrates the use of technical cost model as a decision tool through three examples drawn from the PCB industry. The first example is a comparison of blanking and routing as alternative manufacturing processes for trimming the board to final size. The second example is a comparison of the economics of additive and subtractive technology for PCB fabrication. The last example illustrates how the cost model can be used to guide R&D directions.

Comparison of Blanking and Routing

In the final processing step of PCB manufacturing, the boards are cut from the panel and trimmed to its final shape. Two alternative processes are available for this step: blanking and routing. In blanking, a tool is made according to the desired shape of the board. The tool is then attached to a press and the panel is fed through the tool to produce the final boards. The tool is generally quite expensive, but it can be used for many boards. In routing, which is very similar to drilling, a rotating bit follows the contour of the board to cut the boards out from the panel. The routing bit is very inexpensive, but its useful life is short.

Clearly, the economics of routing and blanking depend on the production volume. Assuming that the yield for both blanking and routing operations is the same, the effect of production volume on the cost per board for a simple double sided board (as described in Table 12) can be estimated using the PCB cost model. The unit cost for blanking is estimated based on a tool cost of $20,000 which lasts 750,000 strikes. A panel is assumed to require 6 strikes which takes a total of 0.6 mins. For routing, the tool costs $4.50 and can cut 4000 linear feet. It is estimated that 2.9 mins is required to route a panel. Figure 12 shows that blanking is only economical above 200,000 boards because of the high cost of the tool. Conversely, because the routing tool is so inexpensive, its cost is independent of production volume.

Table 12: Attributes of Board Used for Cost Analysis

Board Description:

Board Size:	8.45" by 9.50"
Board Thickness:	62 mils
Cu Thickness:	1 oz/sf
No of Layers:	2
No of Holes:	1000 holes (28 mil)
Line Width:	10 mil Lines
Final Yield:	90%
Panel Size:	18" by 21" (4 up)
Laminate:	FR-4 Material ($2.70/sf)

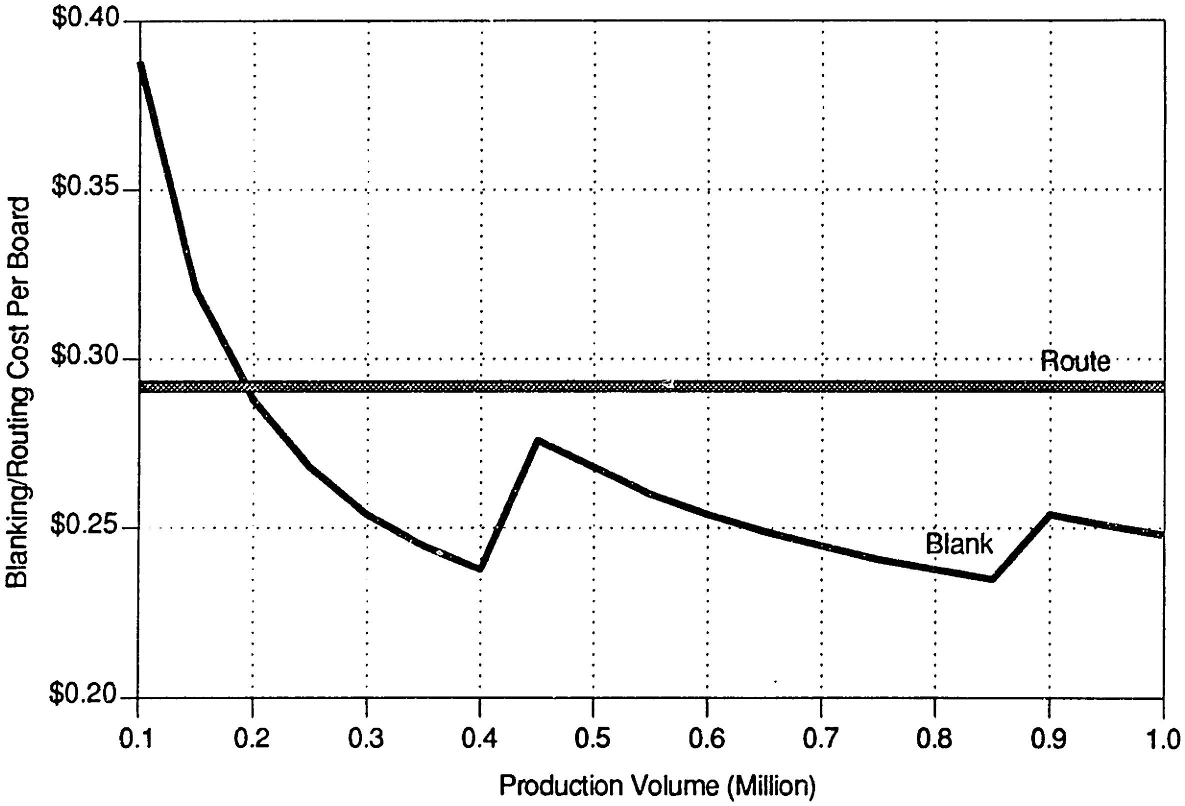


Figure 12: Cost Comparison of Blanking and Routing

Comparison of Additive and Subtractive Technologies

As discussed earlier in this chapter, PCBs can be fabricated using both additive and subtractive technologies. Until recently, additive technology was not considered an alternative due to the inferior properties of the electroless deposited copper. This situation has been changed through process development. Consequently, additive technology is now being evaluated against subtractive technology. Again, the PCB cost model can be used to evaluate the economics of the two technologies. However, the reader is strongly cautioned against taking this example as "absolute truth" because the cost numbers are estimated based on input assumptions, which are very plant specific. To protect the confidentiality of information, list price of chemicals are used, and an estimated overhead rate is used in the cost models. Furthermore, the estimated cost does not include corporate overhead or R&D cost, and therefore, should not be taken as the price of the board. Nevertheless, this example demonstrates the use of cost modeling for technology evaluation.

To make a meaningful cost comparison, it is necessary to establish a base case board. To simplify the analysis, the same double sided board listed in Table 12 is used. All the processing steps for additive and subtractive processes are assumed to be exactly the same, except for electroless and panel plating process. The yield for both processes is assumed to be equal. The breakdown of the estimated board cost fabricated using both technologies is tabulated in Table 13. The results indicated that the additive board would cost $0.10/sq.in. while the same subtractive board would cost $0.11/sq.in. Thus, additive process is cheaper than the subtractive process for the same yield. This is because the subtractive process requires more processing steps; the stripping and etching step alone adds 10% to the total cost.

A more useful cost analysis of additive and subtractive process is to include the effects of yield, which is a strong function of board attributes. For example, it is believed that additive process have higher yield for finer line boards [35]. Using this analysis, the "breakeven point" in terms of yield can be estimated. Unfortunately, empirical data on yield are scarce and highly confidential. Therefore, until such data become available, the analysis cannot be carried any further.

Table 13: Cost Comparison of Additive and Subtractive PCB

Description	Additive	Subtractive
Total Board Cost	$7.77	$8.95
Cost/sq.in.	$0.10	$0.11
<u>Cost Breakdown By Elements:</u>		
Laminates	25%	20%
Process Materials	22%	23%
Capital	16%	13%
Labor	16%	22%
Tooling	5%	4%
Overhead	16%	18%
Total	100%	100%
<u>Cost Breakdown By Process:</u>		
Laminates	25%	20%
Drilling	10%	9%
Imaging	22%	19%
Plating	15%	21%
Electrical Test	1%	1%
Final Inspection	5%	5%
Others	22%	25%
Total	100%	100%

Use of Cost Model To Guide R&D Efforts

Cost modeling can be used as a simulation tool to guide R&D efforts. If the attributes of future products can be estimated, the cost model can be used to simulate their cost and sensitivity analysis can be performed to identify cost drivers and target research efforts. The cost model can also be applied to new products from R&D to investigate their economic competitiveness and processing limitations. The use of the cost model to guide R&D is only limited by the imagination of the users. Thus, the following example is only an illustration of one possible use of the cost model in this capacity.

This example is based on the paper by Charles Lassen presented at the Fall 1989 IEPS Conference [36]. Consider a typical double sided PCB used in computer controllers with attributes listed in Table 14. Under the pressure of miniaturization, it is estimated that a functionally equivalent PCB in 1995 may have the attributes listed in Table 14. The attributes of the 1995 board is derived based on electrical and other processing limitations. The 1995 board has linear dimensions only a quarter of the base case board, a line width of 2 mils and a hole size of 5 mils. Although such a board may not be totally beyond the capability of today's high end board fabrication technology, it is impossible to produce this type of board in high volume with high yield at an affordable cost now. Therefore, the question is: if the 1995 board can be fabricated using today's technology with further process development to improve yield, how much will the board cost? And what are the cost drivers?

To shed light on these questions, the PCB cost model can be used to simulate the cost of both the base case and 1995 board. However, some assumptions have to be made regarding the processing requirements of the 1995 board. The assumptions are:

1. All capital cost were doubled to allow for automation,
2. Process and base material prices were doubled to allow for improved process quality and consistency,

3. Labor rates were assumed to increase from $16 to $20 per hour, corresponding to a 5% increase per year.
4. The yield of the 1995 board is assumed to be 80%, compared to 90% for the base case board,
5. Drill cost is increased to $4.00 per bit. The life of the bit is reduced to 2000 hits with no resharpening, and 2 panels were drilled simultaneously (2 up),
6. 1995 boards are inspected using automatic optical inspection equipment,
7. Both 1995 and base case board are fabricated using additive technology.

Based on these assumptions, the cost of the base case and 1995 board is estimated at $6.93 ($0.17/sq.in) and $6.58 ($2.61/sq.in) respectively. Thus, despite a 64 fold decrease in board area, both boards could be produced at about the same cost, if technology permits. Examination of the cost structure of the 1995 board provides insight into the cost drivers. As shown in Table 15, drilling cost dominates the cost of the 1995 board, running at 58% of total cost. This is a direct consequence of small hole drilling which requires expensive drill bit that cannot be resharpened, and a lower stackup to minimize drill breakage. If the cost of drilling can be reduced by 50%, the resultant board cost is only $3.70. Thus, research into small hole drilling has high potential payoffs.

Another cost driver is the electrical testing of finished boards. Current testing techniques utilize a "bed of nails" fixture, the cost of the fixture being directly proportional to the number of "nails". In the case of the 1995 board fabricated with 64 boards per panel, the cost of these fixtures becomes very high, if it can be manufactured at all (the size and spacing of the nails cannot be reduced beyond a certain limit). Thus, research into new electrical testing technologies, such as non-contact testing, is also crucial.

Table 14: Attributes of Computer Controller Board

Attributes	Base Case	1995
Board Size:	9.25" by 4.38"	2.31 by 1.09
Thickness:	62 mils	16 mils
No of Layers:	2	2
No of Holes:	1400	1400
Diameter:	20 mils	5 mils
Line Widths:	8 mils	2 mils
Final Yield:	90%	80%
Panel Size:	12 by 24 (4 up)	12 by 24 (64 up)
Production:	100,000 boards	100,000 boards

Table 15: Cost Comparison of Base Case and 1995 PCB

Description	Base Case	1995
Total Board Cost	$6.93	$6.58
Cost/sq.in.	$0.17	$2.61
<u>Cost Breakdown By Elements:</u>		
Laminates	22%	3%
Process Materials	19%	3%
Capital	20%	28%
Labor	17%	11%
Tooling	7%	47%
Overhead	16%	8%
Total	100%	100%
<u>Cost Breakdown By Process:</u>		
Laminates	22%	3%
Drilling	14%	58%
Imaging	21%	3%
Electrical Test	2%	20%
Final Inspection	3%	5%
Others	38%	11%
Total	100%	100%

Summary

Technical cost modeling provides a consistent framework for economic analysis. By grounding the cost estimates in engineering knowledge, cost implications of process variables and economics parameters can be captured. The development of the PCB cost model has confirmed the validity of the framework, even when extended to complex multi-step processes which involve wet processing. The resultant cost model is a powerful simulation tool which can not only be used to investigate the economics of using different PCB materials, but also as a decision tool for process and technology evaluations.

One advantage of technical cost modeling over simpler cost estimating techniques is that it not only provides an estimation of the total cost, but also provides a breakdown of the cost of each contributing element. This information can be used to direct efforts at cost reduction, or it can be used to perform sensitivity analyses. The main disadvantage of this approach is that it is time consuming to develop cost estimation model in this manner. However, once the model is developed and verified, it can be used to generate estimates rapidly without the fear of mistakes.

MULTI-ATTRIBUTE UTILITY ANALYSIS

Introduction

Materials selection decisions are rarely made solely on the basis of economics, although economics is definitely an important consideration. In most cases, it is the materials performance that dominates the decision. Once a material is selected for a particular application, however, it becomes very tempting to consider new materials only on the basis of direct substitution, even though the design may not be optimized for the new materials. In the case of a new material offering improvement in one performance characteristic at a higher cost, there are no inherent engineering or economic relationships that dictates the "best" solution; the final decision is made based on how much value the engineer places on the performance characteristic and cost. In some applications, the lower cost alternative may be preferred and vice versa.

One technique to model this decision process is to evaluate the preference of the engineer using a decision analysis technique called multi-attribute utility analysis (MAUA). MAUA is based upon the assumption that it is possible to assign a measure of merit to various combinations of characteristics to reflect the desirability of that set of characteristics. This measure of merit describes the decision maker's preference and the level of preference is expressed in terms of a commensurable metric called the utility. The utility function is defined to be the relationship between the measured levels of a set of characteristics and the merit of that set. The key of MAUA is that it extracts the preference structure of the decision maker and presents it in a mathematical form to permit a rigorous analysis of all alternatives. This is possible because the theory and assumptions of MAUA are founded on principles which can be verified from the data.

MAUA is particularly well suited to multi-objective problems where one action affects many objectives. One such problem is the material selection problem: the selection of one material affects engineering performance, design, manufacturing and economics [37]. Some performance characteristics are pure material properties, but most of them depend on the design and manufacturing process. In the selection of a suitable material in any application, tradeoffs have to be made to achieve a satisfactory solution. By estimating a designer's utility, one can discover the selection criteria employed by the designer. Note that MAUA does not solve the material selection problem; however, it elucidates the preferences of the designer to assist in the decision.

MAUA produces a material neutral ranking system based upon the performance requirements of the application, rather than the available performance from current alternatives. Using the results from MAUA and making some assumptions about performance, various material alternatives can be ranked according to their utility, and the material with the highest utility will represent the preferred alternative. Furthermore, owing to the theory of the utility functions, it is possible to characterize the extent to which these alternatives differ and the effect of a change in characteristics on utility. This capability enables the analyst to identify the extent to which the performance of a particular alternative must change in order to change its competitive position. This information is very useful for assessing new material development efforts.

Theory of Multi-attribute Utility Analysis

The concept of utility is derived from microeconomic theory of demand. Utility is a measure of the relative desirability of an alternative. For two alternatives A and B, the utilities U(A) and U(B) are defined to exhibit the following behavior [38]:

1. If $U(A) > U(B)$, A is preferred to B.
2. If $U(A) = U(B)$, A and B are equally valued.

Utility functions are used to explain demand the same way that production functions are used to explain supply in microeconomics. Unlike production functions, utility functions in microeconomic theory cannot be measured because there are few restrictions on the behavior of individuals and the functional form of the utility functions. However, it is possible to define sub-classes of utility functions which can be measured by making some assumptions about individual behavior. One such class of utility functions that has been successfully employed in operations research and decision analysis is the von-Neumann-Morgenstern utility function [39]. The existence of such a utility function hinges upon the validity of the following six axioms:

1. Complete Preorder - For each possible pair of consequences, one will either prefer one to the other or will find them to be equally preferable.
2. Transitivity of preference - If A is preferred to B and B is preferred to C, then A is preferred to C.
3. Monotonicity of preference - If A is a good thing and $A_1 > A_2$, then A_1 is preferred to A_2. Conversely, if A is a bad thing and $A_1 > A_2$, then A_2 is preferred to A_1.
4. Existence of Probability - In uncertain circumstances, the probability of each possible consequence exists and can be quantified.
5. Monotonicity of Probability - A greater chance of achieving a good outcome is preferred to a lesser chance.
6. Substitution of consequences - If one is indifferent between two outcomes A and B, then these can be substituted for each other in any choice involving uncertain outcomes without changing the choice. This axiom basically implies that individuals have linear preference with respect to probability.

A more thorough discussion of these axioms and their limitations can be found in references [29,40,41]. A consequence of these axioms is that utility can be treated as a cardinal scaling function and its value can be treated analytically. Furthermore, it is possible, within the limits defined by the axioms of utility, to measure the utility function using the following expression:

$$U(\text{Lottery}) = \Sigma\, p_i \bullet U(X_i)$$

Where p_i = The probability of getting the outcome X_i
$U(X_i)$ = The utility of X_i.

The techniques for measuring utility have a common characteristic: they establish an equivalence between a stimulus and a response. The stimulus is usually a binary lottery of the form $(X_1, p; X_2)$, denoting a probability p of getting the outcome X_1 and a complementary probability (1-p) of getting the outcome X_2. The response provided by a person is designed to define a situation of equal value to the stimulus such that it contains no more than one X_i whose utility is unknown. The measurement of utility is analogous to triangulation in surveying [42]. In principle, the measurement procedure can be continued indefinitely to obtained as many readings as desired. The limit on the process is practical.

The most common way to measure von Neumann-Morgenstern utility is the Keeney-Raiffa interview technique. The assessment process usually begins with a short discussion of the purpose of the study and the attributes to be assessed. A questionnaire, which is designed to reveal the designer's intensity of preference for varying levels of a characteristics through the use of lotteries, is then administered to the interviewee.

Theoretically, the above six axioms are sufficient for MAUA. However, the number of questions required for reasonable representation of the MAU function increases exponentially with the number of attributes and can become prohibitively large when the number of attributes increases beyond 5. The practical limit on the number of questions that can treated is 50; beyond this limit, the interviewee is too exhausted to respond meaningfully.

A number of structural assumptions can be invoked to reduce the number of questions required for the assessment. The two most common ones are:

Preferential Independence - An attribute Y is preferentially independent of another attribute Z if the preferences for Y-levels do not depend on a fixed level of Z.

Utility Independence - An attribute Y is utility independent of another attribute Z if the preferences over lotteries on Y-levels do not depend on a fixed level of Z.

Note that utility independence is a specialization of preferential independence assumption. Utility independence implies that the "shape" of the single attribute utility curve does not changes at different levels of other attributes. Therefore, the MAU function can be completely specified by measuring the single attribute utility functions and the scaling coefficients (corner points). These assumptions can be verified during the MAUA interview. If these assumptions can be satisfied, the multiplicative form of the utility function can be used:

$$1 + K \bullet U(X_1,..X_n) = \Pi\, [1 + K \bullet k_i \bullet U_i(X_i)]$$

where K = Normalizing factor
X_i = Level of attribute i
U = Multi-attribute utility
U_i = Single-attribute utility of attribute i
k_i = Scaling coefficient for attribute i

Using this representation, the assessment problem is greatly simplified. If utility independence does not hold, other functional forms of utility and assessment procedure are possible (see reference [40]). A special case of the multiplicative utility representation is when the sum of the scaling factors equals 1.0. In this case, the solution for K degenerates, and the relationship reduces to the additive form given below:

$$U(X_1,..X_n) = \Sigma\, [k_i \bullet U_i(X_i)]$$
$$\text{when } \Sigma\, [k_i] = 1.0$$

This representation of utility is similar to the "weighing factor" approach commonly used in practical economic analyses such as engineering economy. Although this form is easy to use, it does not account for interactions between the attributes. In most cases, the sum of k_i does not equal to 1, implying that the multiplicative form should be used [42]. The multiplicative form is a compromise between the ease of utility measurement (since it can be completely specified by the single attribute utilities and scaling coefficients) and the ability to include attributes interactions.

Procedure of MAUA

The application of MAUA to material selection can be broken down into four major steps: performance evaluation, utility estimation, data reduction, and finally, utility analysis. Each step is briefly discussed in the following sections.

Problem Analysis and Performance Evaluation

In this step, the material application is defined and analyzed. Based on this analysis, a set of important performance characteristics (attributes) of the particular application is identified. The choice of these characteristics is crucial to the analysis. The set of performance characteristics should be chosen with regard to the requirements of the application and not be based on specific materials. For example, the definition of a PCB should not be "a structure consisting of copper conductors in epoxy-glass", but rather, "a structure consisting of conductors embedded in a dielectric medium". In this way, ceramic and polyimide-quartz circuit boards are not excluded. Inputs from industry are very important in determining the appropriate attributes. The number of characteristics chosen must be kept at a reasonable level, preferably less than six, to keep the assessment process under an hour.

Utility Estimation

The heart of the utility assessment process is the design of the questionnaire. It must incorporate questions regarding the attitudes of the interviewee towards critical performance requirements of the application being analyzed. It must also verify the chosen attributes and their ranges. One of the key decisions in designing the questionnaire is the assessment procedure. Two of the most common approaches to measuring individual utility points are certainty equivalent and lottery equivalent.

Figure 13 shows a schematic representation of the two assessment methods. In the certainty equivalent method, the interviewee is presented with a lottery and a fixed (certain) level of performance. Through repeated questioning, the probability p which makes the lottery as attractive as the certain value is determined. Once p is known, an identity in utility can be written, namely,

$$U(\text{Certain Value}) = p \bullet U(\text{Best}) + (1-p) \bullet U(\text{Worst})$$
Because $U(\text{Best}) = 1$ and $U(\text{Worst}) = 0$,
$$U(\text{Certain Value}) = p$$

In the lottery equivalent method, instead of a fixed value, the interviewee is presented with two lotteries. One lottery has a pre-defined probability (usually 0.5) and the interviewee is asked to supply the probability to the other lottery such that he is indifferent towards the two lotteries. Mathematically,

$$0.5 \bullet U(\text{Value}) + 0.5 \bullet U(\text{Worst}) = p \bullet U(\text{Best}) + (1-p) \bullet U(\text{Worst})$$
Because $U(\text{Best}) = 1$ and $U(\text{Worst}) = 0$,
$$U(\text{Value}) = 2p$$

Alternatively, U(Worst) on the left hand side of the above identity can be replaced with U(Best). In this case, the identity becomes:

$$0.5 \bullet U(\text{Value}) + 0.5 \bullet U(\text{Best}) = p \bullet U(\text{Best}) + (1-p) \bullet U(\text{Worst})$$
$$U(\text{Value}) = 2p - 1$$

Lottery Equivalent method is preferred over the simpler certainty equivalent method because it minimizes certainty biases [43]. Certainty biases occur when the interviewees over-value certain outcomes when compared to a probabilistic outcome that has the same utility [44]. This bias induces a systematic shifting of the utility curve, assigning overly high utility values for relatively low levels of performance.

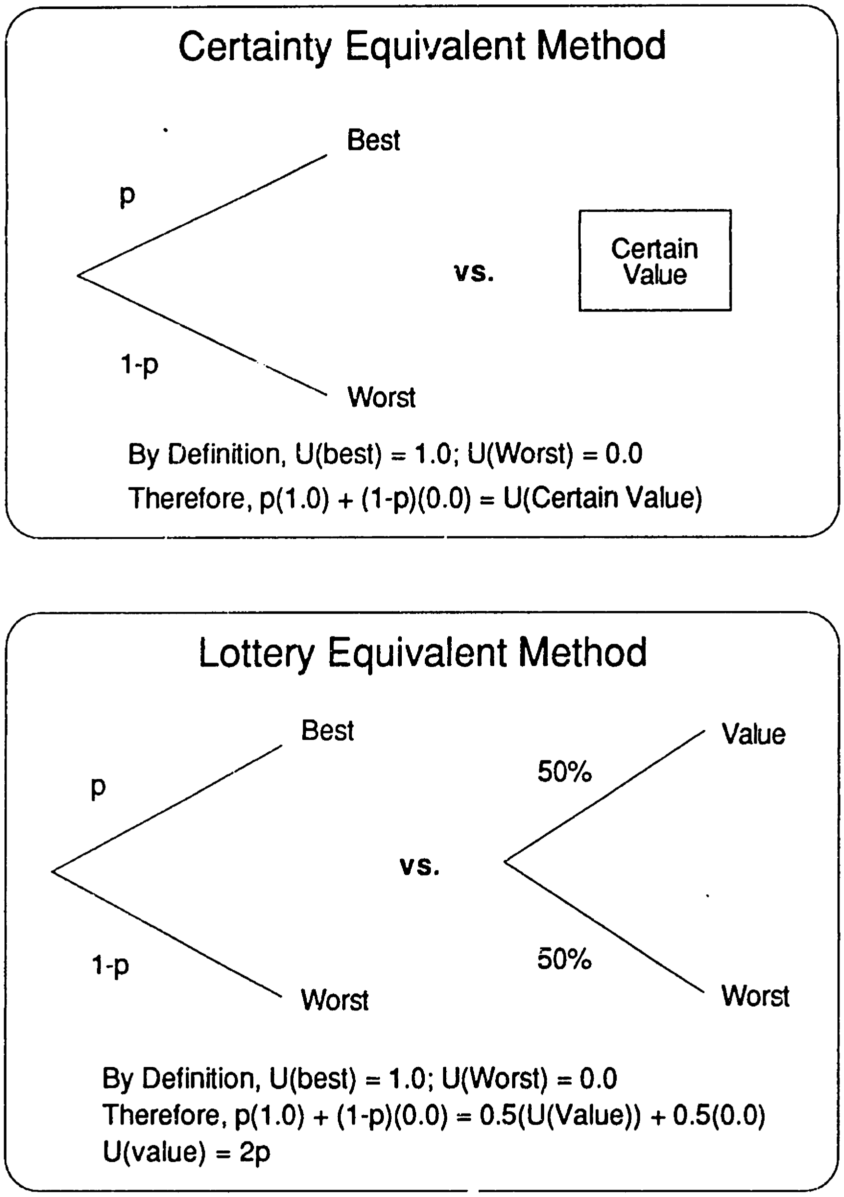


Figure 13: Certainty and Lottery Equivalent Methods

During the MAUA interview, a computer program called ASSESS is available to assist in data collection [45]. The program is capable of using both the certainty and lottery equivalent methods to assess the single attributes and scaling factors. A detailed discussion of questionnaire design can be found in reference [29].

MAUA can be performed with a single designer or a group of designers responsible for material selection. It can also be done individually with different designers for the same application. In this case, there is no guarantee that the measured utility functions will all be the same, since different designers have different perspectives. However, this does not imply that MAUA has no value. The differences in response will reflect differences in perspectives that will be important to uncover. This exercise will prompt the designer to consider the tradeoffs between the various performance characteristics explicitly and bring out the subtle issues and concerns in material selection.

Data Reduction

The completed questionnaire contains sufficient information to construct the interviewee's utility function. The scale of the utility function is defined by two arbitrary points. Conventionally, the best and worst level of X is assigned the value of 1 and 0, respectively. Using the lottery equivalent and the utility equation shown in Figure 13, the unknown utility can be calculated according to the following equation:

Given $(X_i, 0.5; X_*)$ and $(X^*, p; X_*)$

Where $X_i = X$ at i level; its utility is being measure
$X^* = X$ at its best level, by definition $U(X^*)=1$
$X_* = X$ at its worst level, by definition $U(X_*)=0$
p = Probability at which interviewee is indifferent between the two lotteries

Then $0.5 \cdot U(X_i) + 0.5 \cdot U(X_*) = p \cdot U(X^*) + (1-p) \cdot U(X_*)$
Because $U(X^*) = 1$ and $U(X_*) = 0$,
$U(X_i) = 2p$

Similarly, the scaling coefficient can be calculated according to the following equation:

Given $(\underline{X}_i, 0.5; \underline{X}_*)$ and $(\underline{X}^*, P; \underline{X}_*)$

Where $\underline{X}_i$ = Outcome with all its attributes at the worst level except attribute i, which is at its best level
$\underline{X}^*$ = Outcome with all its attributes at its best level, by definition $U(X^*)=1$
$\underline{X}_*$ = Outcome with all its attributes at its worst level, by definition $U(X_*)=0$
p = Probability at which interviewee is indifferent between the two lotteries

Then $U(X_i) = ki = 2p$

In the multiplicative form of the utility function, the normalizing factor K ensures consistency between the definition of $U(\underline{X})$ and the $U(X_i)$. From the definition of $U(\underline{X}) = 1$, and each $U(\underline{X}_i) = 1$ when all the X_i's are at their best levels, the following equation must hold for K:

$$1 + K = \Pi\,[1 + K \bullet k_i)]$$

In general, this expression, which is an (n-1)-dimensional polynomial, must be solved numerically. The determination of K is facilitated by the fact that when $K > 0$, $\Sigma k_i < 1$. Otherwise, K must be between -1 and 0. After the single utilities, the scaling coefficients and scaling factors are calculated, the multiplicative utility function is completely defined by the equation:

$$1 + K \bullet U(X_1,..X_n) = \Pi\,[1 + K \bullet k_i \bullet U_i(X_i)]$$

Linear interpolation between known points can be used to calculate the utility of an alternative with attributes $(X_1,..X_n)$. An alternative to linear interpolation is to fit the single attribute utility data to a mathematical function. The most common form is:

$U(x) = a + b^{(-cx)}$ Where a,b and c > 0

The exponential utility function assumes constant risk-aversion. A person is risk averse if he prefers a certain amount X, to an uncertain situation whose expected value equal EV(X). If one prefers the uncertain situation to the certain amount, he is risk-positive. Similarly, if he chooses according to expected value, he is risk-neutral.

Other forms of utility functions are possible for different risk behavior: linear form for risk-neutral, logarithmic form for decreasing risk-aversion and quadratic form for increasing risk-aversion. The advantage of using a mathematical function for the utility function is convenience; the function is completely specified by only a few constants, two of which are defined by setting the utilities at the best and worst outcomes equal to 0 and 1, respectively. Thus, if excess utility points are measured, regression analysis can be used to calculate the best fit, and confidence levels can be specified. At first sight, this would seem to produce more accurate utility functions. However, the use of pre-defined mathematical functions assumes a specific risk behavior, which may not be true. Therefore, instead of using a mathematical form for the utility function to calculate utilities in this study, linear interpolation is used. In this way, no prior assumptions on risk behavior are made.

Utility Analysis

There are three ways to use the results of utility analysis: ranking of alternatives, comparative evaluation and utility function analysis. To rank the alternatives, the utilities of each alternative are calculated according to their known performance characteristics. Ranking can then be done according to the calculated utilities. This ranking can be used to guide the engineer in material selection. Moreover, new materials and designs can also be compared to current materials and design if they fall within the scope of the measurement.

In comparative evaluation, the question one seeks to answer is: What has to happen to alternative A for it to be better than alternative B? Because of the axioms of utility analysis, the magnitude of the difference in utility indicates the difference in the degree of preference. Therefore, the utility function can be used to estimate the improvement required in a performance characteristic, or cost, to make different alternatives equally attractive.

The utility function, being an analytical function, allows mathematical manipulation for further analysis. For example, iso-utility curves, which are curves of equal utility, can be generated to analyze tradeoff behavior. In addition, the ratio between the partial derivatives of utility with respect to different characteristics can be computed to determine the rate at which the designer trades off one characteristic for another. This information, and the information derived from comparative evaluation, are useful for materials development because it identifies the performance characteristics where improvement has the greatest value to the user.

Discussion

Although multi-attribute utility analysis has been successfully applied to a wide range of problems, including airport siting [46], building code selection [47], water management problems [48], and most recently, materials selection problems [29, 30], its use has not been without controversy. One of the main controversies is the substitution axiom. This axiom is valid only if one's preferences are linear in probability. Research in this area has indicated that people sometimes act as if their preferences are non-linear in probability. Examples include the so-called Allais Paradox [49], and the certainty effect [50]. Nevertheless, recent research indicates that the substitution axiom holds, at least as a first order approximation, except when the probability of some great consequence is either very high or very low.

Many shortcomings of utility analysis can be attributed to fact that it is based on psychometric measurement. The shortcomings are: limited accuracy of data and limited access to experimental subject. Unlike physical measurements, whose accuracy are a function of the experimental design and is amenable to statistical evaluation, utility measurements must involve a human subject. Because humans do not easily distinguish between small differences in probability, there are practical limits on the accuracy of the data. Also implicit in human behavior is the fact that no two people have the same utility function, and that the utility function will change over time.

Furthermore, access to the subject is limited in most practical utility assessments; the analyst is only allowed an hour or two of the decision makers' time because they are usually important people who have a very busy schedule. Because of the limited access to these decision makers and the fact that the utility assessment procedure is very time consuming, it is not possible to collect enough "redundant" data for a statistical analysis of measurement error. This limitation, and the fact that no "true and universal" utility function exists, preclude the development of an error theory for utility measurement. Nevertheless, measures can be taken during and after the interview to check for measurement errors.

During the interview, the analyst must mentally check the consistency of the data and discuss any unusual response with the interviewee. Because the interview process requires the analyst's expertise and judgment, the interview process is done on a face-to-face basis, rather than through the telephone or the mail. After the interview, follow-up questionnaires can be used to check for consistency in response and the validity of the utility independence assumption. The results of the follow-up questionnaire can then be used to assess the quality of the collected data.

Another consequence of limited access to decision makers is that only a limited number of attributes can be analyzed within the allocated time. This reduction in dimensionality to obtain less cumbersome utility model may distort the decision problem. This problem can be minimized by careful selection of the attributes. Attributes can be divided into five groups. They are :

1. **Binary Characteristics** which must be met at a specified level in order for the system to be acceptable, for example, UL approval and impedance control. There is no value to the decision maker in exceeding the specified level, and anything which fails to meet the specification will not be considered for the application.

2. **Insignificant characteristics** for which the overall utility contribution is small or varies so little that it is inconsequential in relation to other characteristics. For example, the CTE in the z-axis for most polymers is in the order of 50 ppm/°C below the glass transition temperature and rapidly increases above the Tg. Therefore, while CTE is an important consideration in general, its value in distinguishing between polymer alternatives is small. Rather, it is the Tg which distinguishes the alternatives.

3. **Aggregable characteristics** which may be converted to a common metric scale or subsumed into related characteristics, e.g. ease of manufacturing is reflected in the cost of a manufactured board, which also captures raw material costs.

4. **Intangible characteristics** whose effects are not easily measured in a consistent or standardized manner and whose causes are not well understood. For example, the reliability of the board can be defined and tested in many ways but no universally acceptable correlation between reliability and other materials characteristics has been obtained (although most experts agree that through plane CTE, which is a function of Tg, has an important effect). Instead of trying to relate Tg to reliability, Tg was used as a proxy attribute in this case study. This allows the decision maker more flexibility in assessing the reliability of a material.

5. **Relevant characteristics** which the decision maker is willing to trade off in the decision process. These attributes should be included in the utility analysis.

The analyst must screen the attributes such that only relevant attributes are included in the analysis. Unlike all the other attributes, relevant attributes are central to the decision problem and the decision makers must consider their tradeoffs to arrive at a satisfactory decision. Thus, despite the limitations of utility analysis, it is very useful as a decision aid to better understand the decision problem and to elucidate tradeoff behavior that otherwise would not be revealed.

Summary

MAUA is an operations research technique which can be used to analyze the technical and economic tradeoffs implicit in the material selection process. Based on interviews with the personnel responsible for selecting materials, this technique yields a quantitative, materials blind measure of the relative value placed on material performance. Because the utility function is defined over a range of performance rather than for specific alternatives, it is possible to use the results to rank very different materials as long as the performance requirements can be satisfied. Furthermore, the theory of utility function allow the identification of how different performance characteristics are traded off against one another, and to what extent the performance of a particular alternative must change for it to be competitive.

This study applies MAUA to two case studies drawn from the electronics industry. It will also extend the application of MAUA by using its results to project market demand. This approach is viable because the utility is a measure of merit for a material aimed at a specific application. Thus, the incorporation of such a measure into the estimation of demand may produce potentially more accurate estimates of demand. In the next chapter, the theory and assumptions of demand analysis is explained.

DEMAND ANALYSIS

Introduction

The last chapter described how multi-attribute utility analysis (MAUA) can be applied to materials selection to reveal the user's perspectives in material selection and to perform sensitivity analysis. Using the results of MAUA, qualitative evaluations of market potentials can be derived, but these results cannot be used to determine how much of each material will be purchased. To estimate the demand for each material, the user's preference, indicated by the utility value, must be translated into a measure corresponding to, or indicating the likelihood of, the actual purchase of that material. This measure is called the purchase potential. The purchase potential measures the tendency of a consumer to undertake an actual purchase, as opposed to utility value, which merely reflects the preference of the user.

Marketing research has shown that utility values can be translated into purchase potential through the use of an appropriate choice model (see Figure 14). Choice models are mathematical formulations that translate preference measures into approximate sales levels. It allows for adjustments based on factors other than preference that may affect the dynamics of purchase. Choice models are derived from the principles of consumer behavior and marketing research, but their validity is evaluated on the basis of observed behavior in market studies. These studies tend to derive aggregated demand from the results of sampling individual purchases. This necessitates the use of non-deterministic (statistical) models. Thus, choice models are frequently statistical models of purchase potential based on utilities.

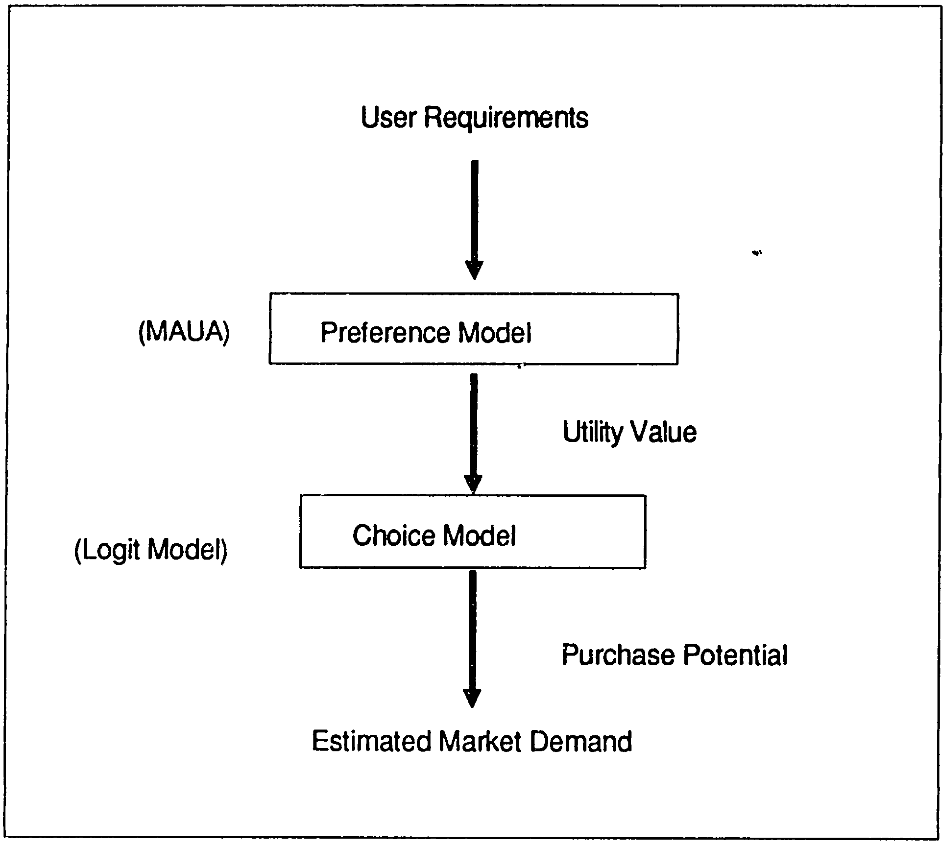


Figure 14: Flowchart for Demand Analysis

Description of Choice Model

Although many choice models (linear probability, probit model) have been proposed in the marketing literature, discussions with marketing research experts and a review of marketing literature revealed that the logit model is the model of choice when accurate estimates of demand are desired [51, 52, 53]. The logit model was developed by McFadden based on the theory of consumer behavior [54].

Suppose an individual has a utility function which can be expressed in the form:

$$U_t = U(X) + \varepsilon(X)$$

Where U_t = utility function of individual
$U(X)$ = nonstochastic utility function
$\varepsilon(X)$ = stochastic elements (error term)

$U(X)$ reflects the "representative" tastes of the population, while $\varepsilon(X)$ reflects the idiosyncrasies of the individual and the random errors in utility measurement. If the errors $\varepsilon(X)$ in the utility values can be assumed to be both independently and identically distributed according to a Weibull distribution, then the probability of selecting alternative A, given measured attributes x and the complete set of all possible alternatives Y, can be expressed by:

$$P(A|X,Y) = \mathrm{Exp}\,[U(A|X)] \,/\, Y'$$

Where $U(A|X,Y)$ = Utility of alternative A, an element of Y, given attributes X
Y' = Sum of the exponential of all utilities over the set Y

The numerator is the exponential of the non-stochastic utility value of the alternative whose selection probability is being estimated. The denominator is the sum of the exponential of all the utilities in the universal set B. The main feature of the logit model is that the relationship between the selection probability and the utility values is exponential in nature. This completes the derivation of the logit model. The reader is referred to reference [54] for a more comprehensive derivation.

Logit models have been applied to the analysis of a wide range of consumer choices, including the selection of college [55], occupational choices [56], and choice of durable consumer products [51, 57]. These models are based on discrete choices which affirm that the consumers select a product (or an option) according to its merit, hence the name discrete choice model [58]. In material selection decisions, however, the assumptions of discrete choice model may not be satisfied. The decision to use a new material is different from the decision to buy a consumer products because of the existence of a *status quo* material, i.e. one that has already demonstrated its applicability. In many cases, there is a large amount of capital invested in the *status quo* material in the form of equipment optimized for processing the material, human learning associated with processing the material, engineering and design efforts based on the material. In other words, there is a cost associated with switching to new materials. Thus, when confronted with new materials, the user will evaluate them against the *status quo* material and decide if the circumstances are justifiable for him to switch to a new material.

Therefore, although discrete choice models have been found to be applicable to consumer products, it is not appropriate for projecting the demand for new materials. Instead, a choice model involving material switching/substitution will be developed for this application. In this case, instead of using absolute utilities for calculating the probability of purchase, the difference between the utility of the *status quo* material and that of the new materials is used. The model will draw on the results of MAUA, logit analysis and markov chain. The result is a framework for analyzing the demand for materials.

Development of Demand Model

In a market where many materials are available, total materials demand can be derived from estimates of the market share of each materials. The market share of each material is a time dependent phenomenon; it depends on market conditions and past material usage. Past material usage, being an indication of market/industry infrastructure, is a good indication of how materials will continue to be used. The materials industry strives for continuity and smooth transition to new materials. Thus, the framework for demand analysis must be capable of relating future market share of materials to past material usage. At the same time, it must have provisions for adjusting the future market share according to the merits of each materials and its purchase dynamics. These requirements prompt the use of a markov chain as the basis for developing the demand model.

A markov chain explicitly considers time dependent phenomenon. A markov process is a stochastic system for which the current state depends only on the immediately preceding state. A markov chain is a special type of markov process used to study the long and short run behavior of stochastic systems. It has been used extensively in queuing theory and their mathematical properties are well understood [59]. Markov chains have also been used to model consumer behavior when product switching is involved [60, 61].

There are two ways to interpret the use of markov chain when estimating the market share of new materials at discrete time intervals. In one interpretation, the markov chain is a non-stochastic flow model describing aggregated material switching behavior [62]. In the other interpretation, the markov chain is stochastic; it yields the estimated market share as a function of the probabilities of switching among the materials. The latter interpretation of the model is used in this analysis to preserve consistency since the logit choice model is stochastic in nature.

In the next few paragraphs, the use of markov chain for demand analysis is presented. Suppose the market share of material i in the market is known. One can define a market share matrix [M], which is a row matrix, where the elements of [M] represent the market share of material i. Next, a square transition matrix [P], whose elements denote the probability of past applications using material i that will switch to material j in the next period, is defined. The transition matrix [P] and the initial market share matrix [M] define a markov chain completely. To estimate the market share of materials for the next period, the following formula can be used:

$$[M]_t = [M]_{t-1} \cdot [P]$$

The transition matrix [P] represents the probability of switching. To estimate demand using markov chains, the transition matrix must be estimated. Since the utility of a material reflects its degree of merit, it is logical to relate the probability of switching to the utility of the materials in the transition matrix [P]. To do so, [P] must satisfy certain conditions of utility analysis. Specifically, utility theory assumes that an alternative with higher utility is preferred to one with lower utility. Therefore, the transition matrix [P] must satisfy the following conditions:

1. If $u_1 < u_2$, $P_{ij} > 0$
   This condition implies that user will switch to a material of higher utility, assuming no transaction cost.
2. If $u_1 > u_2$, $P_{ij} = 0$
   This condition states that user will not switch to a material of lower utility.
3. $\Sigma P_{ij} = 1$ for all i
   This ensures that the probability of switching for all the materials sum up to 1.0

Taking the above conditions into consideration, the probabilities of switching in the transition matrix [P] can be defined as a function of utility differences based on the logit formulation. This yields an exponential relationship between the probability of switching and the utility of the material as given by the equations below:

$$P_{ij} = (1 - P_{ii}).U_{ij} / \Sigma_{i \neq j} (U_{ij})$$

$$U_{ij} = \text{Exp}\,[B.(U_j - U_i)] \qquad \text{For } U_j > U_i$$
$$\phantom{U_{ij}} = 0 \qquad \text{For } U_j \leq U_i$$

where P_{ii} = Probability of not switching
B = Normalizing factor for utility measures

The probability of not switching, P_{ii}, can be interpreted as the inertia to change. It incorporates the effects of transaction cost as a result of the incompatibility of materials to existing processing operations, user idiosyncrasies and other factors. P_{ii} may be estimated from statistical analysis if past market data on material switching is available. Alternatively, a judgmental estimate from industry experts based on market conditions may be used.

The normalizing factor B is necessary to adjust for individual bias in measured utility values when more than one set of utility data is used to estimate aggregate demand. For example, the utility values for one individual may cluster around 0.9 while the utilities of the same materials for others may range from 0 to 1. B can be determined empirically from past market share data using regression analysis. Recall that the utility function is unaffected by positive linear transformation, the utility values of all the alternative materials considered in the analysis may be scaled without any loss of information.

Two properties of the model are worth mentioning:

1. If $(u_j - u_i) < 0$ for all j, then $P_{ii} = 1$
   This implies that no switching will occur if all the new materials j's are perceived to be inferior to the current material i. This is a reasonable assumption.

2. If $(u_j - u_i) > 0$ for some j, then $P_{ii} < 1$
   This is the situation where some of the new materials are perceived to be superior to the current material i and some material substitution will occur. The degree of switching will depend on two factors: the inertia to change P_{ii} and the intensity of preference, expressed by the difference in utilities. The exponential relationship magnifies the effects of switching when the difference in utilities is large. Again, this is a reasonable assumption.

This completes the derivation of the basic demand model. The main feature of this model is the use of a markov chain to relate the future market share of materials to current or past material usage. The future market share is further modified by the probability of switching. This probability is estimated using the logit model, yielding an exponential relation between switching probability and measured utility. The basic demand model assumes that utility is constant and does not change with time. However, this assumption can be suspended if utility data as a function of time is available.

Discussion of Demand Model

The demand model can be used to estimate the demand for materials if data on the utilities of materials and past materials usage are available. Both the market share matrix ($[M]_{n-1}$) and the probability of not switching (P_{ii}) can be estimated from past market data using regression analysis. The utility normalizing factor B can be taken as 1 unless more than one set of utility values are used to estimate aggregated demand. In this case, B may be estimated empirically from past market share data.

Utility measurement is unique to the particular individual, and therefore, demand analysis based on his data will only be indicative of demands by his facility or his company. To get a representative preference structure of the industry, utility data for many individuals must be collected. Next, the utility results must be aggregated in such a way that it remains representative of the industry. There are two ways to accomplish this, depending on the market structure of the industry. In an industry where the relative market share of each company is known, the industry demand can be estimated by summing the individual demand weighted by their market share. Mathematically,

$$[M'] = \Sigma X_k . [M']_k$$

where X_k = Market share of company k
$[M']_k$ = Demand of company k

Another way is to use a nested logit model to estimate the probability of selecting a particular material within a company. Although theoretically sound, this approach is not practical due to data limitation.

Like all predictive marketing models, the demand model is a decision aid, and not a decision substitute. It consists of a set of numerical procedures for processing data and judgement to assist managerial decision; it can be called decision calculus [63]. The demand model is a framework for looking at what utility may imply about demand. It is not possible to use this framework on historical cases of new materials demand because this model requires historical MAU data which are not traditionally measured for market studies. It is also very difficult to test the validity of this demand model because such evaluation requires the design of a closed loop experiment. Such an experimental design is not possible because there are too many control factors. This is a classical limitation in marketing research. However, the framework is presented and applied to a case study so that future work can be built upon this analysis.

Modifications to Basic Demand Model

Secondary effects of materials switching can also be incorporated into the basic model by adjusting the transition matrix. Three effects that are of interest in this study are diffusion, design cycle and marketing effects.

Effects of Diffusion

The effects of diffusion of new products have been extensively reported in marketing research [64]. As more of a new material is used, familiarity with the materials may decrease the resistance to switch to the new material. This effect can be modeled as a diffusion process. Mathematically, diffusion may be modeled by the equation below:

$$P_{ii,t} = 1 - [A + B \cdot M_{i,t-1}] \qquad \text{Where } A, B < 1$$

The factor A can be interpreted as innovative use of new materials, regardless of utilities, while B can be interpreted as imitative use, which increases with the amount of new materials used [64]. This diffusion effect is especially important in estimating the long term aggregate market demand, where the effects of diffusion are more significant.

Design Cycle

Another consideration in materials demand is the design cycle of products. For most commercial electronics products, the incorporation of new materials into new products takes a long time, typically 2-4 years. Thus, when a material is selected for use in the next generation of products, it will take years before the demand for the material actually increases. This delay has a significant impact on demand since actual demand will "lag" the preference/utility model. This effect can be included into the model by lagging the utility values used in the transition matrix.

Effects of Marketing

In the derivation of the transition matrix, it was assumed that the marketing efforts of suppliers have no effect on the potential market for new and current materials. This assumption is not unrealistic in the materials market if the technical support from the suppliers is adequate, because material selection decisions are usually need-based rather than product based. While supplier advertisement and data sheets provide technical specifications of the materials, they only serve as a first step toward material acceptance; most companies have in-house materials laboratories to test the materials. In fact, most users are suspicious of suppliers' data sheets. Instead, new materials are designed based on a company's internal standards. Moreover, since there are only a few new materials introduced into the industry at any one time, it is very unlikely that any user would be unaware of the new materials. Thus, the effects of marketing are assumed to be minimal in the electronic materials market.

In some cases, the effects of marketing may be significant in the estimation of the materials market. In these cases, the marketing variables can be included into the transition matrix by making the probability of switching a function of marketing variables such as price and the levels of advertising [65]. The marketing variables and purchase dynamics are especially important if the intent of demand analysis is to devise a strategic marketing plan.

Summary

In this chapter, a model for estimating the potential demand for new materials based on materials switching was developed. The model introduces utility measurements into a markov chain, based on the framework of logit analysis. The use of MAU values in the model incorporates the effects of preference, uncertainty and risk attitudes into demand projection. The model is a framework for investigating the effects of utility on demand. However, the need for past empirical MAUA data, which is frequently, if not universally, unavailable, and market data, can be a limitation.

CASE STUDY I: COMPUTER AND COMMUNICATIONS INDUSTRY

Introduction

Currently, the computer and communications industry is the largest consumer of printed circuit boards in the U.S. In 1985, this industry consumed 58% of all PCBs manufactured and this percentage is expected to increase to 63% by 1990 (see Table 3). The drive for increased speed in computers has been driving computer manufacturers to design higher and higher performance PCBs. The introduction of surface mount technology (SMT) has further increased the performance requirements of these PCBs. All these developments have motivated the designers to search for better PCB materials.

There are several performance-related requirements for PCB used in the computer and communications industry. These requirements include a good copper surface quality and dimensional stability, a low dielectric constant, a predictable materials through-process performance, a coefficient of thermal expansion (CTE) that matches that of surface mounted devices (SMDs), good thermal performance, and of course, low cost [25]. A material with improved performance in all aspects will be very desirable, but the market acceptance of a material with improved performance in only a few areas is unclear.

In order to understand the materials selection decisions in the computer and communications industry, the methodology proposed in the preceding chapters was applied to this industry. This case study addresses the issue of cost by using the cost model to estimate the cost of PCBs. The tradeoff of performance is elucidated using multi-attribute utility analysis (MAUA). Finally, the potential of new materials in this market is assessed using the demand model described in the previous chapter.

Case Study Description and Background

Materials selection for backpanels in the computer and communications industry was chosen as the basis for this case study to illustrate the proposed methodology. The backpanel, sometimes called backplane, provides interconnections for the daughter boards (PCBs). This application was chosen for the following reasons:

1. As the desired speed of computer increases, signal delay at the board level becomes more important to the overall performance of the computer. Thus, there is a pressing need to improve the performance of PCB through improved design manufacturing changes, and careful selection of materials.

2. The many new materials introduced into the PCB market offer a wide range of properties and cost. To date, despite strong marketing efforts and promises of improved performance, only three materials (epoxy, BT and polyimide) are used in the commercial industry, excluding prototype and microwave application. Of the three materials, epoxy-glass dominates the industry. Although numerous reports have predicted growth for other materials, there is still no clear material winner at this point [66].

3. Although a case study involving the CPU board of computers would be more interesting due to its critical functions, information on CPU boards was not readily available due to its proprietary nature. Therefore, a case study involving backpanels, where information is more readily available, was chosen.

The participants in this study includes Unisys Corporation Control Data Corporation, Digital Equipment Corporation, Wang Laboratories Inc., Apollo Computers (Hewlett Packard) and AT&T Bell Laboratories. The first two participants manufacture mainframe computers (large scale systems). In this market, IBM has the greatest market share [67], but declined to participate in the study. However, since the mainframe market is highly competitive, it is expected that issues facing IBM in terms of materials and technology would be similar to the participants. DEC and Wang are primarily involved in medium and small scale computers. Apollo computers is in the workstation market.

The microcomputer market was not included in this case study because the backplane requirements are very different and the manufacturers would probably be too cost sensitive to allow any meaningful tradeoff analysis. AT&T dominates the communications market, which is a large user of computers. Thus, the companies which participated in the MAUA study span the entire computer industry, providing an interesting cross sectional study of the material selection criterion used in the industry.

Methodology

The MAUA procedure is already described in chapter 4. In the following section, the implementation of each step of the MAUA procedure is discussed.

Problem Definition and Analysis

Because MAUA evaluates alternatives on the basis of their performance characteristics, identification of those characteristics which define and determine the relative competitiveness of these alternatives is critical. Through the examination of engineering literature and discussions with industry representatives, an exhaustive list of performance characteristics was made, including UL approval, dielectric constant, impedance control, dimensional stability, CTE (xy and z direction), glass transition temperature, ease of manufacturing raw material cost, strength of board, reliability of board.

After screening the attributes for binary, insignificant, aggregable and intangible attributes, and consulting with industry experts, the scope of the MAUA was restricted to the following three attributes:

1. Dielectric Constant: This is an important attribute since it is a measure of signal delay of the PCBs. A lower dielectric constant is always preferred.

2. Glass Transition Temperature: This attribute is important because it is an indication of the thermal stability of the PCBs. A high Tg results in a lower variation in CTE during temperature cycling.

3. Cost of Bare Board (Backplane): The cost of backplane is an important factor in material selection. In this case study, the cost of a bareboard was estimated using a PCB cost model developed for this purpose, and the cost estimates were verified by the interviewees. The cost of bare board is a preferred attribute in this case because PCB has very high value added in manufacturing. Therefore, using raw material cost alone can be very misleading.

Questionnaire Design and Administration

After the attributes were selected, a questionnaire was drafted and a pre-interview was set up to validate the attributes selected for analysis and to establish the ranges of the attributes. The current materials used and the job responsibility of the interviewee were also discussed.

The final questionnaire was administered in person and in conjunction with a computer program that automatically brackets the responses. The questionnaire used a scenario of an engineer faced with selecting one of two materials which have uncertain properties, represented by two lotteries with different probability and outcomes. A copy of the questionnaire is included in Appendix A. During the interview, the interviewees were encouraged to discuss the questions with the interviewer. The interview usually did not exceed an hour. Following the interview, the results were analyzed and checked for consistency. A follow-up questionnaire was sent to the interviewee approximately two weeks after the interview. However, not all the interviewees completed the follow-up questionnaire.

Analysis of Results

The raw data and a summary of the results from the follow-up questionnaire for all the interviewees are given in Table 16 and Table 17, respectively.

Table 16: Raw Utility Data For Case Study 1

Subject 1 : Unisys

Single Attribute Utility

D.C.	Utility	Lottery
2.40	1.00	
2.70	0.98	(2.40, 0.99; 4.80) (2.40, 0.50; 2.70)
3.00	0.96	(2.40, 0.98; 4.80) (2.40, 0.50; 3.00)
3.30	0.90	(2.40, 0.95; 4.80) (2.40, 0.50; 3.30)
3.60	0.90	(2.40, 0.95; 4.80) (2.40, 0.50; 3.60)
4.20	0.60	(2.40, 0.80; 4.80) (2.40, 0.50; 4.20)
4.80	0.00	

Tg	Utility	Lottery
120	0.00	
140	0.40	(280, 0.70; 120) (280, 0.5; 140)
160	0.48	(280, 0.74; 120) (280, 0.5; 140)
200	0.84	(280, 0.92; 120) (280, 0.5; 140)
240	0.96	(280, 0.98; 120) (280, 0.5; 140)
280	1.00	

Cost	Utility	Lottery
500	1.00	
1000	0.90	(500, 0.95; 4500) (500, 0.5; 1000)
1500	0.76	(500, 0.88; 4500) (500, 0.5; 1500)
2500	0.60	(500, 0.80; 4500) (500, 0.5; 2500)
3500	0.20	(500, 0.60; 4500) (500, 0.5; 3500)
4500	0.00	

Scaling Coefficients:

D.C.	k1 = 0.40	(Raw Data = 0.70)
Tg	k2 = 0.36	(Raw Data = 0.68)
Cost	k3 = 0.60	(Raw Data = 0.80)

Utility Scaling Factor:

K = -0.6634

Table 16, cont'd

Subject 2 : Unisys

Single Attribute Utility

D.C.	Utility	Lottery
2.00	1.00	
2.70	0.98	(2.00, 0.99; 4.80) (2.00, 0.50; 2.70)
3.40	0.96	(2.00, 0.98; 4.80) (2.00, 0.50; 3.40)
4.10	0.56	(2.00, 0.78; 4.80) (2.00, 0.50; 4.10)
4.80	0.00	

Tg	Utility	Lottery
120	0.00	
140	0.36	(280, 0.68; 120) (280, 0.5; 140)
160	0.40	(280, 0.70; 120) (280, 0.5; 160)
200	0.88	(280, 0.94; 120) (280, 0.5; 200)
240	0.98	(280, 0.99; 120) (280, 0.5; 240)
280	1.00	

Cost	Utility	Lottery
500	1.00	
1500	0.90	(500, 0.95; 4500) (500, 0.5; 1500)
2500	0.84	(500, 0.92; 4500) (500, 0.5; 2500)
3500	0.38	(500, 0.69; 4500) (500, 0.5; 3500)
4500	0.00	

Scaling Coefficients:

D.C.	k1 = 0.84	(Raw Data = 0.92)
Tg	k2 = 0.52	(Raw Data = 0.76)
Cost	k3 = 0.90	(Raw Data = 0.95)

Utility Scaling Factor:

K = -0.9913

Table 16, cont'd

Subject 3 : CDC

Single Attribute Utility

D.C.	Utility	Lottery
2.20	1.00	
2.53	0.96	(2.20, 0.98; 4.80) (2.20, 0.50; 2.53)
2.85	0.90	(2.20, 0.95; 4.80) (2.20, 0.50; 2.85)
3.50	0.74	(2.20, 0.87; 4.80) (2.20, 0.50; 3.50)
4.15	0.40	(2.20, 0.70; 4.80) (2.20, 0.50; 4.15)
4.80	0.00	

Tg	Utility	Lottery
120	0.00	
140	0.20	(280, 0.68; 120) (280, 0.5; 140)
160	0.60	(280, 0.80; 120) (280, 0.5; 160)
200	0.90	(280, 0.95; 120) (280, 0.5; 200)
240	0.92	(280, 0.96; 120) (280, 0.5; 240)
280	1.00	

Cost	Utility	Lottery
500	1.00	
1000	0.96	(500, 0.98; 4500) (500, 0.5; 1000)
1500	0.90	(500, 0.95; 4500) (500, 0.5; 1500)
2500	0.74	(500, 0.87; 4500) (500, 0.5; 2500)
3500	0.40	(500, 0.70; 4500) (500, 0.5; 3500)
4500	0.00	

Scaling Coefficients:

D.C.	k1 = 0.78	(Raw Data = 0.89)
Tg	k2 = 0.40	(Raw Data = 0.70)
Cost	k3 = 0.20	(Raw Data = 0.60)

Utility Scaling Factor:

K = -0.7590

Table 16, cont'd

Subject 4 : DEC

Single Attribute Utility

D.C.	Utility	Lottery
2.50	1.00	
3.00	0.98	(2.50, 0.99; 4.80) (2.50, 0.50; 3.00)
3.50	0.50	(2.50, 0.75; 4.80) (2.50, 0.50; 3.50)
3.80	0.40	(2.50, 0.70; 4.80) (2.50, 0.50; 3.80)
4.10	0.10	(2.50, 0.55; 4.80) (2.50, 0.50; 4.10)
4.80	0.00	

Tg	Utility	Lottery
120	0.00	
140	0.16	(280, 0.58; 120) (280, 0.5; 140)
160	0.20	(280, 0.60; 120) (280, 0.5; 160)
200	0.98	(280, 0.99; 120) (280, 0.5; 200)
280	1.00	

Cost	Utility	Lottery
800	1.00	
900	0.70	(800, 0.85; 1200) (800, 0.5; 900)
1000	0.30	(800, 0.65; 1200) (800, 0.5; 1000)
1100	0.20	(800, 0.60; 1200) (800, 0.5; 1100)
1200	0.00	

Scaling Coefficients:

D.C.	k1 = 0.80	(Raw Data = 0.90)
Tg	k2 = 0.10	(Raw Data = 0.55)
Cost	k3 = 0.02	(Raw Data = 0.51)

Utility Scaling Factor:

K = 0.7923

Table 16, cont'd

Subject 5 : Wang

Single Attribute Utility

D.C.	Utility	Lottery
3.00	1.00	
3.25	0.98	(3.00, 0.96; 4.80) (3.00, 0.50; 3.25)
3.50	0.50	(3.00, 0.96; 4.80) (3.00, 0.50; 3.50)
4.00	0.40	(3.00, 0.96; 4.80) (3.00, 0.50; 4.00)
4.50	0.10	(3.00, 0.60; 4.80) (3.00, 0.50; 4.50)
4.80	0.00	

Tg	Utility	Lottery
120	0.00	
140	0.04	(280, 0.52; 120) (280, 0.5; 140)
160	0.92	(280, 0.96; 120) (280, 0.5; 160)
200	0.92	(280, 0.99; 120) (280, 0.5; 200)
280	1.00	

Cost	Utility	Lottery
300	1.00	
412	0.48	(300, 0.74; 1200) (300, 0.5; 412)
525	0.48	(300, 0.74; 1200) (300, 0.5; 525)
750	0.42	(300, 0.71; 1200) (300, 0.5; 750)
975	0.28	(300, 0.64. 1200) (300, 0.5; 975)
1200	0.00	

Scaling Coefficients:

D.C.	k1 = 0.48	(Raw Data = 0.74)
Tg	k2 = 0.48	(Raw Data = 0.74)
Cost	k3 = 0.02	(Raw Data = 0.51)

Utility Scaling Factor:

K = 0.0800

Table 16, cont'd

Subject 6 : Apollo

Single Attribute Utility

D.C.	Utility	Lottery
2.00	1.00	
2.35	0.96	(2.00, 0.98; 4.80) (2.00, 0.50; 2.35)
2.70	0.84	(2.00, 0.92; 4.80) (2.00, 0.50; 2.70)
3.40	0.70	(2.00, 0.85; 4.80) (2.00, 0.50; 3.40)
4.10	0.04	(2.00, 0.52; 4.80) (2.00, 0.50; 4.10)
4.80	0.00	

Tg	Utility	Lottery
120	0.00	
140	0.98	(280, 0.99; 120) (280, 0.5; 140)
280	1.00	

Cost	Utility	Lottery
324	1.00	
824	0.88	(324, 0.94; 2160) (324, 0.5; 824)
783	0.72	(324, 0.86; 2160) (324, 0.5; 783)
1242	0.70	(324, 0.86; 2160) (324, 0.5; 1242)
1701	0.16	(324, 0.58; 2160) (324, 0.5; 1701)
2160	0.00	

Scaling Coefficients:

D.C.	k1 = 0.60	(Raw Data = 0.80)
Tg	k2 = 0.80	(Raw Data = 0.90)
Cost	k3 = 0.20	(Raw Data = 0.60)

Utility Scaling Factor:

K = -0.8780

Table 16, cont'd

Subject 7 :AT&T

Single Attribute Utility

D.C.	Utility	Lottery
2.00	1.00	
2.35	0.90	(2.00, 0.95; 4.80) (2.00, 0.50; 2.35)
2.70	0.90	(2.00, 0.95; 4.80) (2.00, 0.50; 2.70)
3.40	0.90	(2.00, 0.95; 4.80) (2.00, 0.50; 3.40)
4.10	0.02	(2.00, 0.51; 4.80) (2.00, 0.50; 4.10)
4.80	0.00	

(Note that Tg is not used as an attribute here; Impedance control is used instead)

%Ohm	Utility	Lottery
5	1.00	
7.5	0.40	(5, 0.70; 10) (5, 0.5; 10)
10	0.00	

Cost	Utility	Lottery
350	1.00	
400	0.90	(350, 0.95; 750) (350, 0.5; 400)
450	0.70	(350, 0.58; 750) (350, 0.5; 450)
550	0.60	(350, 0.80; 750) (350, 0.5; 550)
650	0.60	(350, 0.80; 750) (350, 0.5; 650)
750	0.00	

Scaling Coefficients:

D.C.	k1 = 0.20	(Raw Data = 0.60)
%ohm	k2 = 0.02	(Raw Data = 0.51)
Cost	k3 = 0.90	(Raw Data = 0.95)

Utility Scaling Factor:

K = -0.5825

Table 17: Results of Follow-up Questionnaire

In the follow-up questionnaire, the subject is asked to indicate his preference given a set of performance characteristics for materials A and B. The following section tabulates the response. An asterisk is used to indicate responses that do not agree with the calculated utilities.

Subject 1

Calculated Utilities		Subject's
U(A)	U(B)	Preference
0.72	0.74	B
0.66	0.84	B
0.66	0.52	A
0.85	0.43	A
0.32	0.78	B

Subject 2

Calculated Utilities		Subject's
U(A)	U(B)	Preference
0.971	0.973	B
0.905	0.960	B
0.904	0.900	A
0.953	0.830	Indifferent *
0.945	0.946	B

Subject 3

Calculated Utilities		Subject's
U(A)	U(B)	Preference
0.76	0.72	A
0.33	0.67	B
0.50	0.50	A *
0.76	0.68	A
0.30	0.78	B

Subject 5

Calculated Utilities		Subject's
U(A)	U(B)	Preference
0.40	0.42	A *
0.50	0.42	B *
0.91	0.91	A *
0.12	0.59	B
0.39	0.94	A *

Subject 6

Calculated Utilities		Subject's
U(A)	U(B)	Preference
0.48	0.52	A
0.07	0.74	B
0.78	0.22	A
0.81	0.52	B
0.77	0.92	A *

Subject 4 and 7

Follow-up Questionnaire Not Returned

In this study, a reference lottery with best and worst outcomes were pitted against one with best and intermediate outcomes. The utility of the intermediate outcome can be calculated by using the following equations:

Given $(X^*,p;X_*)$ and $(X^*,0.5;X_i)$

Where $X^* = X$ at its best level, by definition $U(X^*)=1$
$X_* = X$ at its worst level, by definition $U(X_*)=0$
$X_i = X$ at intermediate level i; its utility is being measure
p = Probability at which interviewee is indifferent between the two lotteries

Then $U(X_i) = 2p - 1$

There are two sources of uncertainty in the calculated utilities: the uncertainty in utility measurement and the uncertainty in materials performance. The accuracy of utility measurement is limited by the human factor and the time limit of interviews as discussed in Chapter 5. The uncertainty in materials performance can be represented as a lottery in the utility calculations. For example, suppose the caluclated single attribute utility for Tg at 120°C and 140°C is 0.2 and 0.4 respectively. If a material has a 80% probability of exhibiting a Tg of at 140°C and a 20% complementary probability of exhibiting a Tg of 120°C, then its single attribute utility for Tg is 0.36.

From the data, the MAU function was constructed using linear interpolation. Next, the utility for the three most commonly used materials were calculated. In this analysis, the calculated utilities do not include the uncertainties in materials performance due to the lack of such information from the users. Table 18 list the utilities calculated based on average industry taken from suppliers' data sheets listed in Table 19. The costs were estimated using the PCB cost model based on a typical 14 layer board for mainframe computer applications, and a typical 8 layer board for lower end computer systems applications.

Table 18: Results of MAUA

Company	EG	BT	Polyimide	CE
Unisys	0.66	0.84*	0.83	0.89
Unisys	0.91	0.96*	0.95	0.98
CDC	0.52	0.68*	0.67	0.86
DEC	0.09	0.16	0.17*	0.51
Wang	0.12	0.79	0.85*	0.89
Apollo	0.08	0.69	0.81*	0.92
AT&T	0.62*	0.52	0.47	0.27

* Currently available material with the highest utility

Table 19: Average Properties of Laminates

Attributes	Epoxy	BT	Polyimide	CE	PTFE
Tg (°C)	125	181	260	245	75
E (1 Mhz)	4.5	4.1	4.3	3.5	2.94
Cost					
8 layers	$330	$430	$571	$688	$1432
14 layers	$690	$860	$1200	$1400	$2800

Results and Findings

In the following sections, the results of MAUA are analyzed according to the segments of the industry served by the participants.

Large Scale Computer Industry

BT blend has the highest utility for almost all the interviewees in the large scale computer industry. The utility of polyimide follows BT closely, while that of epoxy-glass trails by a much larger margin. If the dielectric constant of polyimide were 4.2 (which is what some suppliers claim) instead of 4.3, its utility would be higher than that of BT. Thus, it can be concluded that both polyimide and BT are very attractive and their use will continue to grow in this applications until a better material becomes available.

From Table 20, which computes the percentage improvement of dielectric constant and glass transition temperature required to offset a 1% increase in cost, it is apparent that the attribute of most concern is the dielectric constant. In all cases, the Tg of polyimide is deemed adequate, as evident from the larger percentages in the table. A small percentage indicates that a small improvement in performance is required to justify the cost increase, implying that the attribute is critical. This table is useful for identifying research direction for improving the desirability of these materials.

Medium and Small Scale Computer

In the medium and small scale market, the results from the interviews indicated that polyimide is preferred. Although polyimide may actually be preferred due to its higher Tg, it is believed that the ranking results from the measured cost insensitivity due to measurement errors. These errors were confirmed for the interviewees at Wang where the follow-up questionnaire indicated numerous inconsistencies (see Table 17). The explanations for these errors, and possible remedies, are discussed later in this chapter.

Table 20: % Change in Performance Needed to Offset 1% Change in Cost

	EG	BT	Polyimide
Unisys			
Dielectric Constant	-0.07	-0.16	-0.15
Glass Transition Temp	0.14	0.22	2.46
Unisys 2			
Dielectric Constant	-0.13	-0.11	-0.15
Glass Transition Temp	0.41	0.31	6.64
CDC			
Dielectric Constant	-0.00	-0.01	-0.01
Glass Transition Temp	0.03	0.02	0.11
DEC			
Dielectric Constant	-0.02	-0.22	-0.15
Glass Transition Temp	0.66	0.15	5.69
Wang			
Dielectric Constant	-0.41	-0.01	-0.10
Glass Transition Temp	0.46	0.01	0.12
Apollo			
Dielectric Constant	-0.03	-0.06	-0.07
Glass Transition Temp	0.00	0.00	0.05
AT&T			
Dielectric Constant	-81.7	-78.0	-65.4

The results of MAUA for DEC indicated that both polyimide and BT are favored. DEC's interviewee indicated that a high Tg is critical for their applications. His concern with Tg is augmented by the fact that DEC's PCBs tend to have very high layer counts. DEC started using polyimide for its PCB in 1985. Therefore, they have in-house manufacturing and design knowledge which reduces their uncertainties with respect to cost and performance in the final products. However, BT has already been designed into their new products.

Based on these results, it is expected that both polyimide and BT will continue to be used in this market, but the search for a cheaper material will continue. The market will probably move towards the high Tg, low E materials, but at a slower pace than the mainframe market since it is more cost sensitive. As computer technology advances, the mainframe technology today will become the medium scale technology of tomorrow. Therefore, this market will follow the footsteps of the mainframe market in term of materials requirements.

Communications Industry

In this industry, cost is the main concern. Therefore, inexpensive epoxy-glass is preferred. Tg was not a concern to the interviewee in the current design. Information from other departments at AT&T confirmed the utility results, although the PCBs designed for more critical applications have already moved to the higher Tg materials. It is estimated that more than 99% of all the PCBs used by AT&T are epoxy-glass.

Implications for New Materials

The MAUA results indicated that the computer industry favors high Tg materials such as polyimide and BT, while the communications market prefers epoxy-glass for its low cost. Among the new materials targeted at high performance PCB applications, cyanate ester (under the trade names N-8000 by Nelco and CE-245 by Norplex/Oak) and PTFE have the greatest potential. It is expected that PTFE will continue to fill a niche market in the extremely high performance market due to its high cost and the capital investment in new equipment required to process it. The potential of cyanate ester in the commercial market depends on its pricing policy and manufacturing requirements. To date, no supplier has committed to commercial pricing. Preliminary evaluation of the materials indicates good compatibility with existing manufacturing equipment.

To investigate the effect of cost on utility, the utility of each material alternative can be plotted as a function of the final cost of the baseline circuit for each interviewee, holding all other physical characteristics fixed. Figure 15 shows the utility versus cost plot for an interviewee. Where market price data exists, the point corresponding to the current production cost is indicated. These results from all the interviewees suggest that low Tg laminates with low dielectrics, such as X-0096 (Fortin Industries) and Gore-Tex (Gore Composites Inc.), are unlikely to make headway into the high performance PCB market where active components are soldered because of the Tg limitations. However, their use in backplanes with press-fit connections is plausible. Research on these materials should focus on improving their Tg values. The results also suggest that, if the CE board were to cost less than $2,200, its utility would exceed that of polyimide, the current high utility alternative. This type of plot can be generated for each interviewees to investigate their cost-performance tradeoffs.

Through the use of the PCB cost model, this analysis can be taken further. Given a targeted bare board price, it is possible to evaluate the cost of the laminate and prepreg that would yield a board at that price. This analysis can be used for cyanate ester. Although the material has generated a great deal of interests, its price has not yet been fixed by suppliers. There is, however, a general consensus that CE laminates will be priced at the level of polyimide laminates, but speculation on yield is less unanimous.

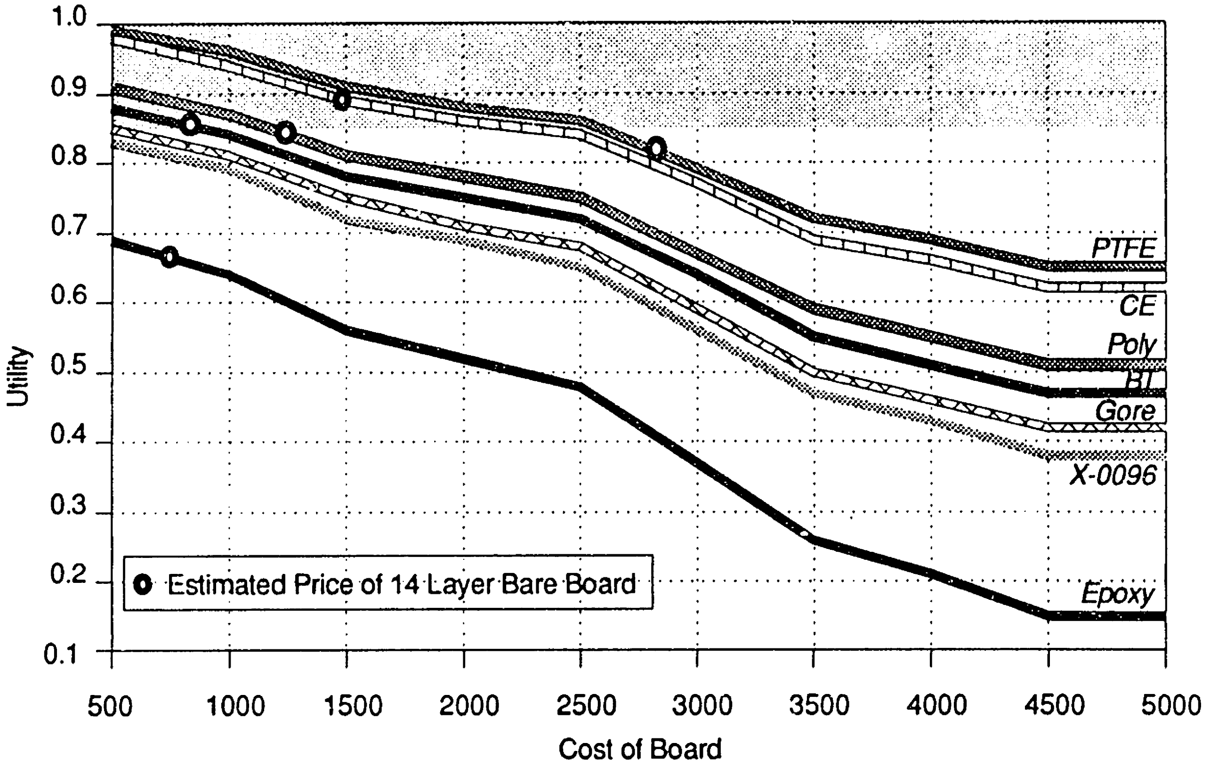


Figure 15: Effect of Cost On Utility

By making assumptions regarding yield and processing parameters (as recommended by suppliers, but <u>not</u> verified by users), it is possible to establish the combinations of new material price and processing yield required to achieve the necessary bare board price. A graph presenting the results of this analysis is presented in Figure 16.

The gray area is delimited by 60% yield as the minimum acceptable yield which a board manufacturer would be willing to countenance, while 90% yield is a credible upper limit for 14 layer board yields in EG. Note that for the same raw material cost, the CE board is cheaper than the polyimide board at the same yield due to the difference in lamination temperature. As the figure indicates, almost all combinations of yield and price would make cyanate ester a viable competitor in the high performance end of the market place.

Demand Analysis

The MAUA has provided some insight into the material requirements of new materials in the PCB industry targeted at computers and communications applications. Utility is an indication of "goodness" of the materials and the resulting materials ranking is very useful in making material selection decisions. However, a material with high utility may not necessarily result in high demand; there are other factors such as inertia of the industry, compatibility of new materials with existing manufacturing capabilities, design cycles and other factors that affect materials demand. This section will utilize the demand analysis discussed earlier to estimate the demand of new materials in the PCB industry.

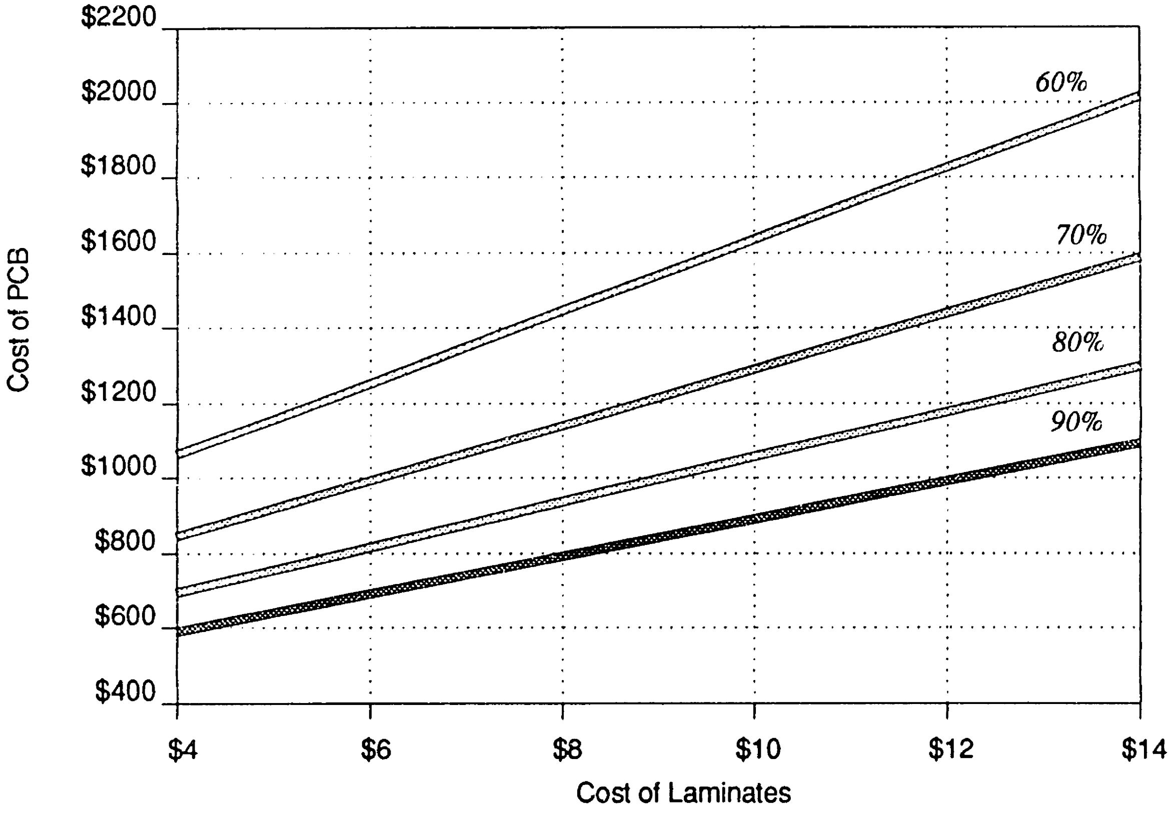


Figure 16: Estimated Cost of CE PCBs as a Function of Yield

Recall that the transition matrix [P] and the initial market share row vector [M] define a markov chain completely. To estimate the market share of materials, the following formula can be used:

$$[M]_n = [M]_{n-1} \cdot [P]$$

The transition matrix [P] can be estimated by the utilities of the materials by the following equations:

$$P_{ij} = (1 - P_{ii}) \,.\, U_{ij} / \Sigma\, (U_{ij})$$

$$U_{ij} \begin{array}{ll} = \exp\,[B \,.\, (u_j - u_i)] & \text{For } u_j > u_i \\ = 0 & \text{For } u_j \leq u_i \end{array}$$

where P_{ii} = Probability of not switching
B = Normalizing factor for utility measures

For the purpose of this study, B is taken as 1.0 because each interviewee's utility function is used to estimate demand at his facility only. The effects of diffusion are neglected in this analysis because the models are not used to estimate long term market demands. Moreover, in the technologically competitive electronics industry, the change of utilities will be very rapid, rendering the use of current utility measurements for long term projections inappropriate and deceptive.

To estimate P_{ii} and the market share matrix for materials, past materials usage of the companies involved in this study has to be collected. This is achieved through a survey of the companies that participated in the study (These data are not available in published literature). The results of the survey are summarized in Table 21. In all cases, these data are estimated by the engineer who participated in the MAUA interviews because actual data are either not available from the company or considered confidential. The survey results indicate that most companies are not using any significant quantity of the higher performance laminates.

Table 21: Survey Results from the MAUA Participants

Large Scale Industry	Epoxy	polyimide	BT
1984	75%	0%	25%
1986	60%	0%	40%
1988	50%	0%	50%
Medium Scale Industry	Epoxy	polyimide	BT
1984	100%	0%	0%
1986	99%	1%	0%
1988	98%	1%	1%
Small Scale Systems	Epoxy	polyimide	BT
1984	100%	0%	0%
1986	100%	0%	0%
1988	100%	0%	0%
Communications	Epoxy	polyimide	BT
1984	100%	0%	0%
1986	100%	0%	0%
1988	100%	0%	0%

From the results of the survey, P_{ii} is estimated to be 0.8 for large scale computer manufacturers and 0.98 for medium scale computer manufacturers, except for the highest utility material where it has to be 1.0 for consistency. The transition matrices are calculated for all the participants and tabulated in Table 22. PTFE was excluded in the matrix because it is used only in very specialized applications. Therefore, the decision to use PTFE is not considered in the same way as the decision to switch from epoxy to BT or polyimide.

A few points about the transition matrix are worth mentioning. First, the results in Table 22 indicate that there is an almost equal probability for switching from epoxy laminates to polyimide and BT for all the participants except AT&T. This is because all participants value the combinations of properties of BT and polyimide almost equally.

Table 22: Transition Matrix for the Participants

Large Scale System	Epoxy	Polyimide	BT
Epoxy	0.8	0.1	0.1
Polyimide	0.0	1.0	0.0
BT	0.0	0.2	0.8

Medium Scale System	Epoxy	Polyimide	BT
Epoxy	0.8	0.1	0.1
Polyimide	0.0	1.0	0.0
BT	0.0	0.2	0.8

Small Scale System	Epoxy	Polyimide	BT
Epoxy	0.98	0.01	0.01
Polyimide	0.0	0.8	0.2
BT	0.0	0.0	1.0

Communications	Epoxy	Polyimide	BT
Epoxy	1.0	0.0	0.0
Polyimide	0.2	0.8	0.0
BT	0.1	0.1	0.8

In using the demand analysis framework, a time period of 4 years was used, i.e. only the 1984 data are used to project 1988 market share and only 1988 data are used to project 1992 market share for each company. The four year period was selected because it is longer than the design cycle of most computers, and the utility function can be assumed to be valid over the time frame. The results of the demand analysis, assuming that only epoxy, polyimide and BT are available in the market, are summarized in Table 23 and discussed with respect to the scale of the industry.

Large Scale System: Using a estimated market composition of 75% epoxy and 25% BT, demand analysis yield a market composition of 60% epoxy, 32.5% BT and 7.5% polyimide in 1988, and 48% epoxy, 40% BT and 12% polyimide for 1992. Although the 1988 composition differs from the survey results, discussion with the interviewee indicated that the survey results may be too optimistic for BT.

Table 23: Estimated Potential Market Composition Using Demand Analysis
(Only Epoxy-Glass, Polyimide and BT are Available in the Market)

Large Scale System	Epoxy	Polyimide	BT
1984	75%	0%	25%
1988	60%	7.5%	32.5%
1992	48%	12%	40%
Medium Scale System	Epoxy	Polyimide	BT
1984	100%	0%	0%
1988	98%	1%	1%
1992	96%	2%	2%
Small Scale System			
Not computed due to errors in data			
Communications	Epoxy	Polyimide	BT
1984	100%	0%	0%
1988	100%	0%	0%
1992	100%	0%	0%

Note that the interviewees in large scale systems are heavily involved in prototyping and manufacturing new products which would most likely involve new materials. The estimated data are plant specific demand, not sales values.

Medium Scale System: The survey results indicated that there is a strong inertia to switch to new materials. Using $P_{ii} = 0.98$ yields an estimated 2% market for both BT and polyimide in 1992.

Small Scale System: As discussed, the measured MAU function is not the true MAU function due to measurement errors. Since the demand analysis assumes that the MAU function is true and correct, the analysis cannot be applied here with confidence.

Communications: This is the trivial case where the current material (epoxy-glass) will continue be used since it has the highest utility. Survey results indicated that the company has no desire to switch to new materials. Therefore, until technological advances drive them to change their utility, only epoxy-glass will continue to be used.

The previous analysis assumes that no new materials are introduced into the market. One of the newest PCB materials is cyanate ester (CE). Given the performance levels of CE and an estimated cost of $1,500 for a 14 layer backplane, the utility of this material can be calculated. Table 24 shows the transition matrix recalculated based on the estimated utility of cyanate ester. In the next table (Table 25), the potential market of this material, given its combination of performance characteristics, is estimated. One observation from the Table 25 is that cyanate ester has great potential in large scale systems. The same can be said about medium scale systems, although the magnitude is smaller.

Table 24: Estimated Transition Matrix If Cyanate Ester is Available

Large Scale Industry	Epoxy	Polyimide	BT	CE
Epoxy	0.80	0.06	0.07	0.07
Polyimide	0.00	0.80	0.00	0.20
BT	0.00	0.10	0.80	0.10
CE	0.00	0.00	0.00	1.00
Medium Scale Industry	**Epoxy**	**Polyimide**	**BT**	**CE**
Epoxy	0.980	0.006	0.006	0.008
Polyimide	0.000	0.980	0.008	0.012
BT	0.000	0.000	0.980	0.020
CE	0.000	0.000	0.000	1.000

Table 25: Estimated Potential Market For Cyanate Ester Using Demand Analysis

Large Scale Systems	Epoxy	Polyimide	BT	CE
1984	75%	0%	25%	0%
1988	60%	8%	33%	0%
1992	48%	10%	31%	11%
Medium Scale Systems	**Epoxy**	**Polyimide**	**BT**	**CE**
1984	100%	0.0%	0.0%	0.0%
1988	98%	1.0%	1.0%	0.0%
1992	96%	1.1%	1.1%	1.8%

Comparing Table 25 with Table 23, it is found that cyanate ester will grow at the expense of polyimide and BT, but does not affect the market for epoxy. Although this analysis makes assumptions about market inertia and the price of the CE PCBs, it does not make the assumption that the market for epoxy-glass is not affected by the introduction of CE. The latter outcome is a result from the demand analysis. Note that this analysis assumes a specific price ($1,500) for the CE boards. If the price level changes, so will the results of this analysis.

Discussion of Limitations in Methodology

MAUA is a useful tool for analyzing material selection problem because of its ability to quantify preference and tradeoffs. The utility assessment procedure not only provides information for the construction of a utility function, but it is also an excellent way to discuss materials concerns by defining the scope of the problem and focusing the concerns of the engineers. However, MAUA has many setbacks too. It is a relatively time consuming procedure and some expertise is required before one can obtain meaningful results.

One of the most difficult problems of this case study was the measurement of the interviewee's sensitivity to cost. The scenario presented to the designer leads him to assume that the material selection process is at the initial evaluation level. Thus, he is more concerned with performance, whereas as the project approaches actual production, cost, manufacturing feasibility, product reliability and production yield will assume greater importance. In fact, the responses in the follow-up questionnaire indicated that the interviewees are actually more cost sensitive than the MAUA results indicated.

Another possible reason for the measured cost insensitivity is the construction of the lotteries in the questionnaire. Since the only reference lottery contained the worst outcome, which is usually highly undesirable, the assessment of cost becomes very biased as the interviewees try to avoid the possibility of having the worst outcome at all cost. Future assessment used the worst outcome in both lotteries to minimize bias. A direct cost performance tradeoff technique may also be used in conjunction with the lottery equivalent technique to estimate the scaling factors.

The use of a follow-up questionnaire is very useful in checking the validity of utility independence and the consistency of the utility response during the interview. However, it is difficult to convince all the interviewees to complete the follow-up questionnaire promptly. Nevertheless, the follow-up questionnaires which were returned indicated that the assumptions were valid and the measured utility functions are representative of their preference. The results from the follow-up questionnaire also confirmed the effects of certainty bias. In most cases, it was found that the interviewees are willing to pay more for a certain outcome than a probabilistic outcome that has the same utility.

The application of demand analysis to this case study allowed an investigation of the effects of utility on materials demand for different market scenarios. It also identified some problems with using demand analysis for this case study. One of the biggest problem is the limited availability of data on past material usage of PCBs. This necessitates the estimations of the probability of not switching (P_{ii}) and the materials market share matrix; regression analysis cannot be used here due to lack of data. Note that demand analysis only true if utility does not change over the time period used. In a fast moving industry, this assumption may not hold.

Conclusions

This study has illustrated that the proposed methodology can be to analyze tradeoffs in materials selection in the computers and communications industry. The methodology combines credible manufacturing models with market perceptions which enable the analyst to identify processing and production goals which must be met before users will consider using new materials. By focusing on material performance, rather than specific material alternatives, the analyst is free to evaluate the response of PCB material consumers to speculative developments, enabling him to determine the viability of alternative materials strategies in advance of major financial commitments. The study has also identified some problems of the methodology and modifications were made to improve the result of the second case study.

The analysis found that the computer industry favors high Tg materials such as polyimide and BT, while the communications market prefers epoxy-glass for its low cost. Among the new materials targeted at high performance PCBs, cyanate ester (under the trade names N-8000 by Nelco and CE-245 by Norplex/Oak) and PTFE have the greatest potential. It is expected that PTFE will continue to fill a niche market in the extremely high performance market due to its high cost and the capital investment in new equipment required to process it. The potential of cyanate ester in the commercial market depends on its pricing policy and manufacturing requirements. Whether the growth of cyanate ester would occur at the expense of other high performance materials, or whether it would open new markets will depend upon how the material is ultimately marketed.

CASE STUDY II: MATERIALS FOR STANDARD ELECTRONIC MODULES

Introduction

Although the defense industry consumes only about 20% of all PCBs produced, it has a strong influence on the development of "leading edge" PCB materials and technology. Therefore, a case study selected from the military industry provides insight into the requirements of new PCB materials which may be helpful for new materials development efforts. There is also the potential of eventual commercialization of new materials from military research when the materials are better characterized and their cost is lower.

The case study selected for detail analysis is the materials selection problem for Standard Electronic Modules (SEM) in "E" format. The same methodology described earlier will be applied to the SEM "E" module to assess the competitive position of new materials for this application. The results from this case study are a ranking of current materials and speculations on new materials in terms of the changes required from a particular alternative for it to be competitive.

Description of Case Study

The SEM "E" module was chosen as the basis of this case study because it provides a consistent framework for comparison between companies. Moreover, it is a material neutral specification, allowing both new and speculative materials to be analyzed. This study focussed on the materials for the substrate, which may be organic or inorganic, and the cold plate. However, the cold plate and the substrate was not be treated separately in this study; rather, the entire module was considered as an optimized materials and design combination. The chips and single chip packages were <u>not</u> included in the analysis.

Figure 17 shows the SEM "E" module used as the basis for this case study. The module will be used to house a processor for the next generation of avionics equipment for airplanes (or even satellites). The processor is expected to operate at a rate of up to 5 mips. Leadless hermetic ceramic chip carriers may be used in the module. The CTE of the substrate, which is a circuit board, and the cold plate may have to be matched to that of the ceramic chip carriers to improve the reliability of the solder joints.

There are many ways to control the CTE of the substrate. The simplest solution is to used a substrate which has a low CTE. Examples of low CTE substrates are ceramic circuit boards, organic epoxy-Kevlar and polyimide-quartz boards. Another solution is to use a low CTE and high modulus cold plate/heat sink, usually called the constraining core, to control the CTE of the module. The constraining core, when rigidly bonded to cheap epoxy-glass or polyimide-glass boards, provides CTE control to the module. Examples of constraining core materials are copper-invar and copper-molybdenum alloys; newer systems include graphite and silicon carbide (SiC) reinforced aluminum. In this case study, both low CTE substrate and low CTE cold plate construction will be considered

In order to make this case study manageable, numerous simplifying assumptions have to be made. In this study, a 12 layer organic board with 1800 20-mil holes and 6 mil lines will be used as the basis for all performance and cost estimates. A dielectric thickness of 6 mils is assumed, giving a board thickness of 82.8 mils (if a dielectric thickness of 5 mils is possible, the board thickness will be 71.8 mils). For the inorganic board, an 8 layer construction is assumed to be adequate and functionally equivalent to the 12 layer organic board. Using a 40 mil alumina substrate, this yields a board thickness of 76.5 mils.

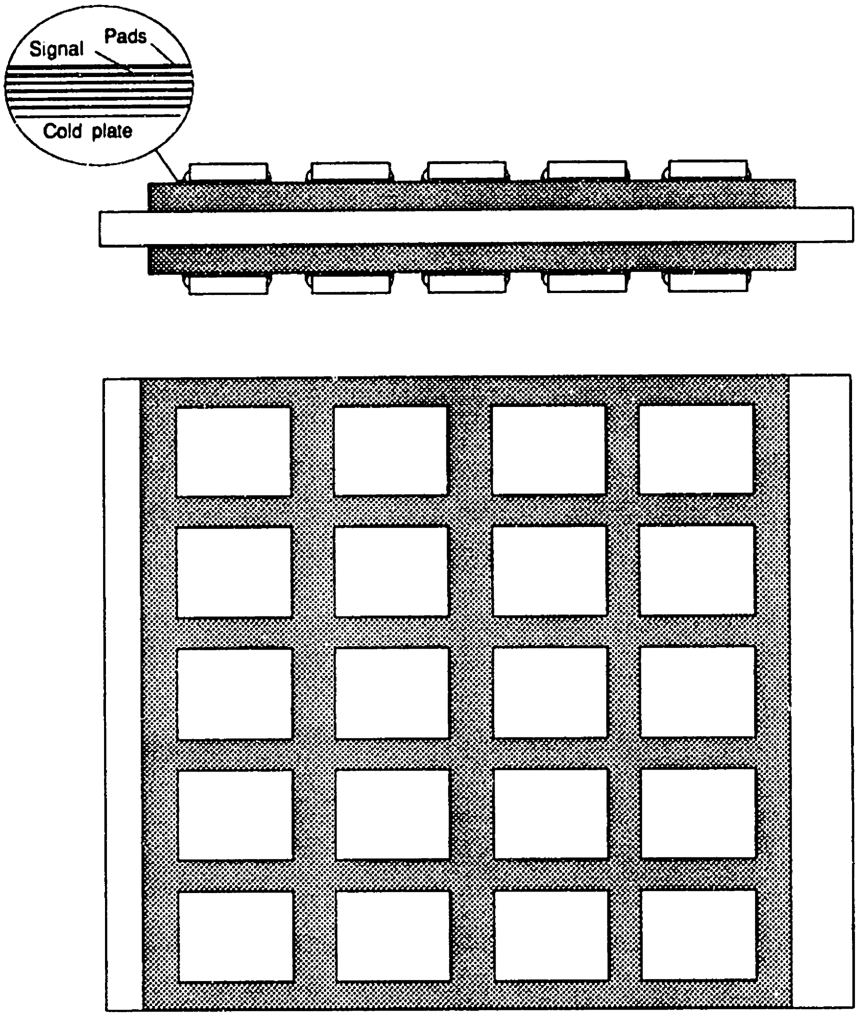


Figure 17: Standard Electronics Module "E" Format

The ceramic green tape alternative is evaluated based on a 40 mil alumina substrate construction, but an assessment of the green tape construction without the alumina substrate is also given. The thickness of the heat sink for SEM "E" module ranges from 60 mils to 80 mils, depending on the board materials and thermal requirements. In general, ceramics are used with a thinner heat sink because of its superior thermal conductivity and vibration characteristics.

Attribute Selection

After the application has been specified, the next step is to identify the attributes or performance characteristics which must be included in the analysis. Although the use of more attributes may describe the problem better, the number of attributes which can be included in an analysis is limited to a maximum of six to keep the interview session below two hours.

The relevant attributes or performance characteristics for selecting materials for SEM "E" modules were determined after a review of technical literature, trade journal and consultation with industry experts. First, an exhaustive list of performance characteristics was made. The list was then trimmed down after a careful analysis for binary, aggregable insignificant and intangible attributes, and a discussion with each interviewee. Finally, the scope of the MAUA was restricted to the following four attributes:

1. <u>Dielectric Constant:</u> This attribute is a measure of signal delay of the PCBs. A lower dielectric constant is always preferred.

2. <u>Coefficient of Thermal Expansion (CTE):</u> This attribute affects the reliability of the solder joints between the ceramic chip carriers and the substrate. When leadless ceramic chip carriers are used, the CTE is even more critical since there are no leads to compensate for the difference in CTE between the chip carrier and the substrate. Thus, a CTE close to that of the chip carrier is preferred.

3. Weight: This attribute is important in avionics applications where every pound of weight saved in the equipment can be used for carrying additional payload.

4. Cost of Bare Module: Ideally, the life cycle cost would be the best attribute to capture the economic implications of using different materials. However, it is impossible to estimate such cost without a detailed knowledge of the specific program for which the module is designed. Since the focus of this study is the trends in materials selection and requirements, using a specific program for the case study is too limiting. As a proxy attribute, the cost of the module is used. This attribute is preferred to raw materials cost because SEM modules have very high value added in manufacturing.

One very important consideration in materials selection for these modules is the thermal conductivity of the substrate and cold plate materials. In this study, the thermal conductivity of the materials is not used as an attribute because the heat dissipation requirement is usually dictated by the maximum junction temperature (usually 110°C). This requirement must be satisfied regardless of the materials used. Therefore, it is binary in nature; there is usually no value to the user in exceeding the specification.

Junction temperature is a strong function of the components used and board design. Without an exact specified design, the junction temperature cannot be calculated. Since the objective of this case study is to understand trends and performance tradeoffs, material conductivities are not used as an attribute but their effects are incorporated as a second order effect on weight and cost. Thus, this study approaches the problem of thermal requirements by using equivalent thermal efficiency rather than thermal conductivity. In some cases, one may have to use a different type of cold plate or design thermal vias into the PCB to satisfy the thermal constraints. This will affect the cost and weight of the module.

Before one can calculate the utilities of the various alternatives, the values of the attribute and the cost of each alternative must be estimated. The next section describes the approach to performance and cost estimation.

Estimation of Cost and Performance

Dielectric Constant

The dielectric constant (E) of a material is a function of many factors, such as signal frequency, temperature and humidity. In a circuit, the effective E is dependent on circuit construction (stripline vs microstrip). In this case study, the dielectric constant refers to the measured average value for the material at 1 Mhz. The values are directly extracted from suppliers' brochures. Whenever possible, the value is verified with the user.

Coefficient of Thermal Expansion (CTE)

The CTE of the module is a function of the properties and thickness of substrate materials and the heat sink. It can be estimated using finite element method (FEM) or closed form analytical equations based on the laminated plate theory. In this study, the following approximation is used:

$$\alpha' = \Sigma \alpha E t / \Sigma E t$$

Where α' = Estimated CTE of composite (module)

α = CTE of a composite layer

E = Modulus of elasticity of the composite layer

t = Thickness of the composite layer

The equation has been found to approximate the actual CTE very well, although the predicted CTE tends to be higher than the measured average CTE [68]. In order to use the above equation to estimate the CTE of the module, the following assumptions are made about the adhesive used to bond the substrate to the cold plate:

1. When the CTE of the substrate is lower than that of the heat sink (e.g. alumina on aluminum), the adhesive is assumed to the "flexible", which decouples the systems.

2. When a low CTE heat sink is used (e.g. epoxy-glass on copper-invar), the adhesive is assumed to be rigid. Thus, the CTE of the module will be lower than that of the substrate alone.

Figure 19 shows the effects of heat sink thickness on the CTE of the module for a coupled system (polyimide on low CTE heat sink). The CTE of the module decreases with increasing cold plate thickness. Note that the Al/SiC cold plate is not as effective as CIC, CMC and Al/graphite in reducing the CTE of the module.

Weight

The weight of the module is a function of the thickness and density of the substrate and heat sink. Figure 18 shows the effects of heat sink thickness on the weight of the module. The weight of the module increases with the thickness of the cold plate. The increase is especially drastic with the copper/CIC and copper/CMC cold plates. In the utility analysis, the thickness of the heat sink is dictated by the thermal requirements; thus, a thicker copper/invar plate would have to be used in place of a copper/molybdenum plate to achieve the same thermal efficiency.

Cost of Bare Module

The cost of the module is very difficult to estimate because it is a strong function of its physical characteristics and its manufacturing process. Currently, the costs estimated by the interviewees are used as the basis for comparison. In some cases where this information is not available, the cost of the module is estimated by using a combination of cost model estimates and the cost of heat sink quoted by third party vendors.

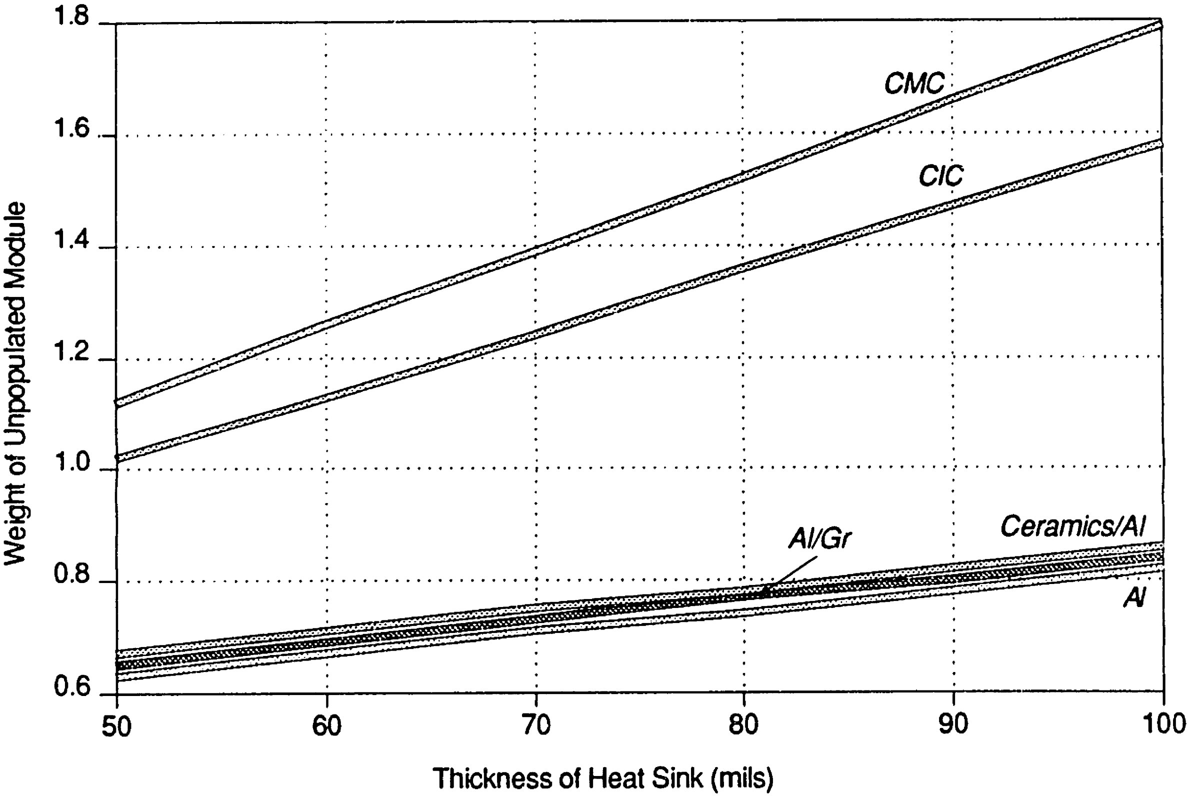


Figure 18: Effect of Cold Plate Thickness On Weight of Module

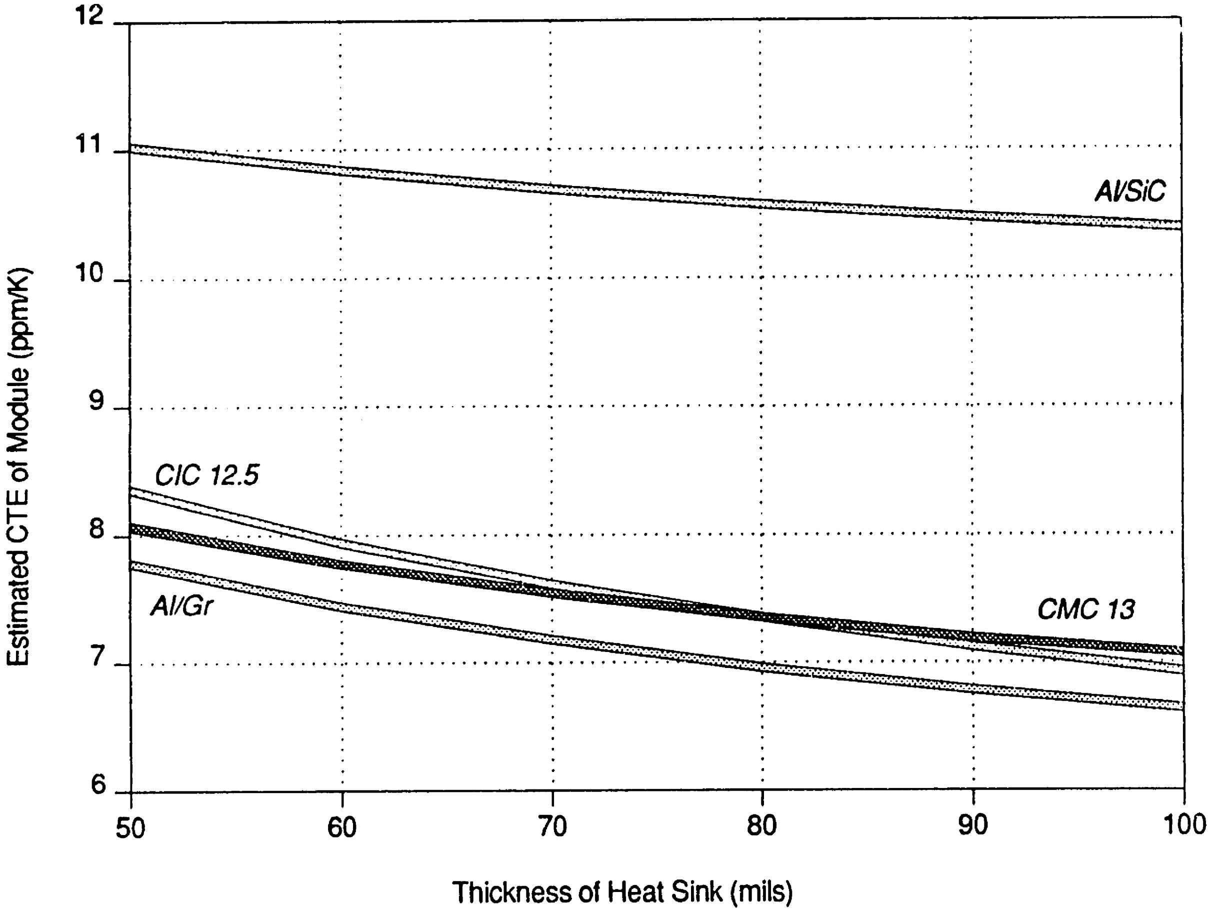


Figure 19: Effect Cold Plate Thickness On CTE of Module

The cost of an organic board is estimated from the PCB cost model and verified by the interviewees. Table 26 shows the estimated cost of PCB built from different materials, assuming a 12 layer PCB fabricated with 2 boards per panel and a yield of 85% on both the panels and innerlayers.

The cost of ceramic boards were estimated based on sources from the industry. It was assumed that a thick film ceramic board costs $5.00 per square inch per layer, while a cofired green tape board costs $2.50 to $4.00 per square inch per layer. This gives an 8-layer board cost of $1,260 and $640 to $1024 for a thick film and green tape board, respectively. For the green tape, an average cost of $800 per substrate is used in this analysis.

Based on the above estimates and inputs from the industry, the performance of a SEM "E" module built from several alternative substrate and cold plate materials is tabulated in Table 27.

Table 26 : Estimated Cost of SEM "E" PCBs

Process	EG	PG	PQ	EK(120)	EK(108)
Laminates	12%	25%	62%	53%	81%
Drilling	8%	7%	10%	7%	3%
Imaging	32%	21%	8%	15%	6%
Lamination	23%	31%	12%	13%	5%
Inspection	11%	7%	3%	5%	2%
Others	14%	9%	5%	7%	3%
Total %	100%	100%	100%	100%	100%
Total Cost	$153	$251	$620	$334	$817

Table 27: Average Properties of SEM "E" Module

Materials	Dielectric Constant	CTE	Weight	Cost
Thick Film (Alumina) Aluminum Heat Sink (Thickness = 60 mils)	8.0	7.9	0.80	$2,670
Green Tape (Ceramic) Aluminum Heat Sink (Thickness = 60 mils)	8.0	7.9	0.71	$2,170
Epoxy-Kevlar Aluminum Heat Sink (Thickness = 68 mils)	3.6	8.0	0.7	$2,500
Polyimide-Kevlar Aluminum Heat Sink (Thickness = 68 mils)	3.5	6.0	0.7	$2,700
Polyimide-Quartz Aluminum Heat Sink (Thickness = 68 mils)	3.6	10.1	0.72	$3,200
Polyimide-Glass Aluminum Heat Sink (Thickness = 68 mils)	4.3	13.4	0.71	$1,000
Epoxy-Glass Copper/Invar Heat Sink (Thickness = 80 mils)	4.5	7.5	1.36	$1,320
Epoxy-Glass Copper/Moly Heat Sink (Thickness = 70 mils)	4.5	7.3	1.39	$1,600
Polyimide-Glass Copper/Invar Heat Sink (Thickness = 80 mils)	4.3	7.30	1.36	$1,710
Polyimide-Glass Copper/Moly Heat Sink (Thickness = 70 mils)	4.3	7.55	1.39	$2,000

Results of MAUA Interviews

The questionnaire used during the utility assessment interview is included in Appendix B. The companies which participated in this study are:

1. Hughes Aircraft
2. Martin Marietta
3. Texas Instruments
4. Raytheon
5. Rockwell

The raw data collected from interviews with engineers from these companies are tabulated in Table 28. The data are presented such that it does not identify individual companies as per the request of the participants. The results of the follow-up questionnaire are also summarized in Table 29. Again, not all interviewees returned the follow-up questionnaire. Based on the estimated values of the attributes in Table 27, the utility of each alternative can be calculated (see Chapter 4 for equations) and the alternatives can be ranked according to their utilities as shown in Figure 20. Given the current price levels, epoxy-Kevlar and polyimide-Kevlar on aluminum module have the highest utility for all the interviewees. Four out of five interviewees rank the ceramic green tape systems above the CIC/CMC PCBs, but below the Kevlar-based organic PCBs. A high CTE organic PCB mounted on low CTE core, such as polyimide-glass on CIC, is also not as attractive as the Kevlar-based system due to its high weight. Polyimide-glass on aluminum is even less preferred; only one out of four prefer polyimide on aluminum over on a low CTE core. It was also found that polyimide-quartz on aluminum is not an attractive option to 4 out of 5 interviewees. This is somewhat surprising in view of the attention received by this material in the past few years. The main shortcomings of PQ is its high cost, and a relatively high CTE of 10 ppm/°C. The rankings discussed above are based on the attributes listed in Table 27; if the value of the attributes changes, so will the rankings.

Table 28: Raw Utility Data For SEM "E" Case Study

Subject 1

Single Attribute Utility

D.C.	Utility	Lottery
3.00	1.00	
4.00	0.90	(3.00, 0.45; 8.00) (4.00, 0.5; 8.00)
5.00	0.70	(3.00, 0.35; 8.00) (5.00, 0.5; 8.00)
6.00	0.60	(3.00, 0.30; 8.00) (6.00, 0.5; 8.00)
7.00	0.50	(3.00, 0.25; 8.00) (7.00, 0.5; 8.00)
8.00	0.00	

CTE	Utility	Lottery
6.00	1.00	
8.00	0.40	(6.00, 0.20; 14.00) (8.00, 0.5; 14.00)
9.00	0.30	(6.00, 0.15; 14.00) (9.00, 0.5; 14.00)
10.00	0.02	(6.00, 0.01; 14.00) (10.00, 0.5; 14.00)
14.00	0.00	

Weight	Utility	Lottery
0.70	1.00	
0.80	0.80	(0.70, 0.40; 1.40) (0.80, 0.5; 1.40)
1.00	0.66	(0.70, 0.33; 1.40) (1.00, 0.5; 1.40)
1.20	0.10	(0.70, 0.05; 1.40) (1.20, 0.5; 1.40)
1.40	0.00	

Cost	Utility	Lottery
$1,000	1.00	
$2,000	0.70	(1000, 0.35; 4000) (2000, 0.5; 4000)
$3,000	0.60	(1000, 0.30; 4000) (3000, 0.5; 4000)
$4,000	0.00	

Scaling Coefficients:

D.C.	k1 = 0.30	(Raw Data = 0.15)
CTE	k2 = 0.50	(Raw Data = 0.25)
Weight	k3 = 0.50	(Raw Data = 0.25)
Cost	k4 = 0.50	(Raw Data = 0.25)

Utility Scaling Factor:

K = 0.972

Table 28 cont'd

Subject 2

Single Attribute Utility

D.C.	Utility	Lottery
3.00	1.00	
4.00	0.98	(3.00, 0.49; 8.00) (4.00, 0.5; 8.00)
6.00	0.98	(3.00, 0.49; 8.00) (6.00, 0.5; 8.00)
8.00	0.00	

CTE	Utility	Lottery
6.00	1.00	
8.00	0.98	(6.00, 0.49; 14.00) (8.00, 0.5; 14.00)
10.00	0.98	(6.00, 0.49; 14.00) (10.00, 0.5; 14.00)
12.00	0.10	(6.00, 0.05; 14.00) (12.00, 0.5; 14.00)
14.00	0.00	

Weight	Utility	Lottery
0.60	1.00	
0.80	0.98	(0.60, 0.49; 1.40) (0.80, 0.5; 1.40)
1.00	0.50	(0.60, 0.25; 1.40) (1.00, 0.5; 1.40)
1.20	0.05	(0.60, 0.10; 1.40) (1.20, 0.5; 1.40)
1.40	0.00	

Cost	Utility	Lottery
$500	1.00	
$1,000	0.80	(500, 0.40; 4000) (1000, 0.5; 4000)
$2,000	0.60	(500, 0.30; 4000) (2000, 0.5; 4000)
$3,000	0.40	(500, 0.20; 4000) (3000, 0.5; 4000)
$4,000	0.00	

Scaling Coefficients:

D.C.	k1 = 0.50	(Raw Data = 0.25)
CTE	k2 = 0.50	(Raw Data = 0.25)
Weight	k3 = 0.50	(Raw Data = 0.25)
Cost	k4 = 0.40	(Raw Data = 0.20)

Utility Scaling Factor:
K = 0.890

Table 28 cont'd

Subject 3

Single Attribute Utility

D.C.	Utility	Lottery
3.00	1.00	
4.00	0.90	(3.00, 0.45; 8.00) (4.00, 0.5; 8.00)
5.00	0.80	(3.00, 0.40; 8.00) (5.00, 0.5; 8.00)
6.00	0.60	(3.00, 0.30; 8.00) (6.00, 0.5; 8.00)
8.00	0.00	

CTE	Utility	Lottery
6.00	1.00	
8.00	0.90	(6.00, 0.45; 12.00) (8.00, 0.5; 12.00)
9.00	0.80	(6.00, 0.40; 12.00) (9.00, 0.5; 12.00)
10.00	0.60	(6.00, 0.30; 12.00) (10.00, 0.5; 12.00)
12.00	0.00	

Weight	Utility	Lottery
0.60	1.00	
0.80	0.90	(0.70, 0.45; 1.40) (0.80, 0.5; 1.40)
1.00	0.80	(0.70, 0.40; 1.40) (1.00, 0.5; 1.40)
1.20	0.06	(0.70, 0.03; 1.40) (1.20, 0.5; 1.40)
1.40	0.00	

Cost	Utility	Lottery
$1,000	1.00	
$2,000	0.70	(1000, 0.35; 4000) (2000, 0.5; 4000)
$3,000	0.60	(1000, 0.30; 4000) (3000, 0.5; 4000)
$4,000	0.00	

Scaling Coefficients:

D.C.	k1 = 0.20	(Raw Data = 0.10)
CTE	k2 = 0.50	(Raw Data = 0.25)
Weight	k3 = 0.40	(Raw Data = 0.20)
Cost	k4 = 0.40	(Raw Data = 0.20)

Utility Scaling Factor:

K = 0.726

Table 28 cont'd

Subject 4

Single Attribute Utility

D.C.	Utility	Lottery
3.00	1.00	
4.00	0.70	(3.00, 0.35; 8.00) (4.00, 0.5; 8.00)
5.00	0.60	(3.00, 0.30; 8.00) (5.00, 0.5; 8.00)
6.00	0.40	(3.00, 0.20; 8.00) (6.00, 0.5; 8.00)
8.00	0.00	

CTE	Utility	Lottery
6.00	1.00	
8.00	0.70	(6.00, 0.35; 12.00) (8.00, 0.5; 12.00)
9.00	0.40	(6.00, 0.20; 12.00) (9.00, 0.5; 12.00)
10.00	0.38	(6.00, 0.19; 12.00) (10.00, 0.5; 12.00)
12.00	0.00	

Weight	Utility	Lottery
0.60	1.00	
0.80	0.80	(0.70, 0.40; 1.40) (0.80, 0.5; 1.40)
1.00	0.50	(0.70, 0.25; 1.40) (1.00, 0.5; 1.40)
1.20	0.00	

Cost	Utility	Lottery
$1,000	1.00	
$2,000	0.80	(1000, 0.40; 4000) (2000, 0.5; 4000)
$2,500	0.56	(1000, 0.28; 4000) (2500, 0.5; 4000)
$3,000	0.40	(1000, 0.20; 4000) (3000, 0.5; 4000)
$4,000	0.00	

Scaling Coefficients:

D.C.	k1 = 0.36	(Raw Data = 0.18)
CTE	k2 = 0.56	(Raw Data = 0.28)
Weight	k3 = 0.36	(Raw Data = 0.18)
Cost	k4 = 0.40	(Raw Data = 0.20)

Utility Scaling Factor:

K = 0.819

Table 28 cont'd

Subject 5

Single Attribute Utility

D.C.	Utility	Lottery
3.00	1.00	
4.00	0.90	(3.00, 0.45; 8.00) (4.00, 0.5; 8.00)
5.00	0.80	(3.00, 0.40; 8.00) (5.00, 0.5; 8.00)
6.00	0.70	(3.00, 0.35; 8.00) (6.00, 0.5; 8.00)
8.00	0.00	

CTE	Utility	Lottery
6.00	1.00	
8.00	0.80	(6.00, 0.40; 12.00) (8.00, 0.5; 12.00)
9.00	0.50	(6.00, 0.25; 12.00) (9.00, 0.5; 12.00)
10.00	0.40	(6.00, 0.20; 12.00) (10.00, 0.5; 12.00)
12.00	0.00	

Weight	Utility	Lottery
0.60	1.00	
0.80	0.90	(0.70, 0.45; 1.40) (0.80, 0.5; 1.40)
1.00	0.90	(0.70, 0.45; 1.40) (1.00, 0.5; 1.40)
1.20	0.06	(0.70, 0.03; 1.40) (1.20, 0.5; 1.40)
1.40	0.00	

Cost	Utility	Lottery
$1,000	1.00	
$2,000	0.80	(1000, 0.40; 4000) (2000, 0.5; 4000)
$3,000	0.70	(1000, 0.35; 4000) (3000, 0.5; 4000)
$4,000	0.00	

Scaling Coefficients:

D.C.	k1 = 0.40	(Raw Data = 0.20)
CTE	k2 = 0.80	(Raw Data = 0.40)
Weight	k3 = 0.60	(Raw Data = 0.30)
Cost	k4 = 0.60	(Raw Data = 0.30)

Utility Scaling Factor:

K = 0.997

Table 29: Results of Follow-up Questionnaire

In the follow-up questionnaire, the subject is asked to indicate his preference given a set of performance characteristics for materials A and B. The following section tabulates the response. An asterisk is used to indicate responses that do not agree with the calculated utilities.

Subject 1
Calculated Utilities

U(A)	U(B)	Subject's Preference
0.807	0.767	A
0.758	0.730	A
0.753	0.812	B
0.755	0.634	B *
0.737	0.745	B

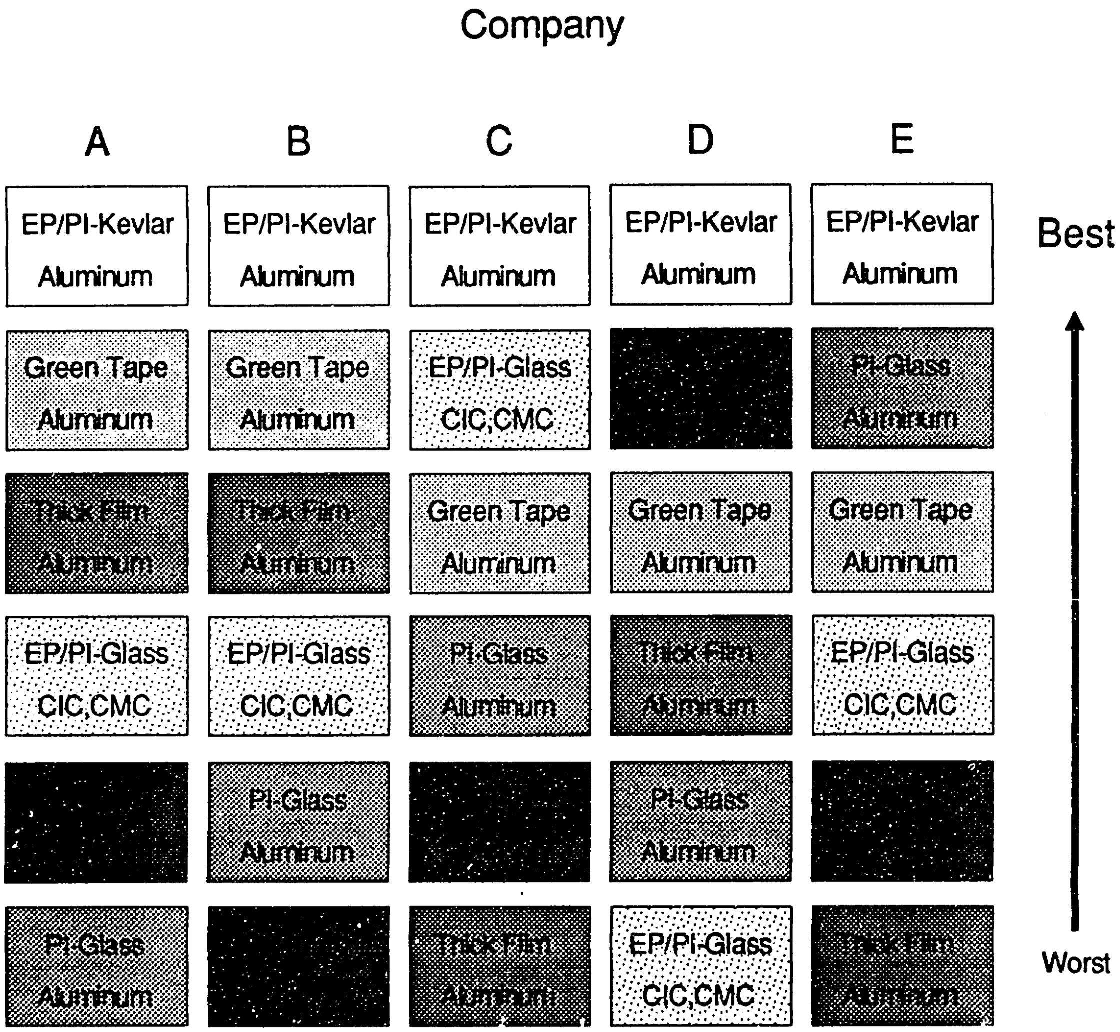
Subject 2
Follow-up Questionnaire Not Returned

Subject 3
Follow-up Questionnaire Not Returned

Subject 4
Follow-up Questionnaire Not Returned

Subject 5
Calculated Utilities

U(A)	U(B)	Subject's Preference
0.965	0.914	A
0.964	0.948	A
0.940	0.945	B
0.903	0.961	B
0.940	0.941	B



A	B	C	D	E
EP/PI-Kevlar Aluminum	EP/PI-Kevlar Aluminum	EP/PI-Kevlar Aluminum	EP/PI-Kevlar Aluminum	EP/PI-Kevlar Aluminum
Green Tape Aluminum	Green Tape Aluminum	EP/PI-Glass CIC,CMC	[illegible]	PI-Glass Aluminum
Thick Film Aluminum	Thick Film Aluminum	Green Tape Aluminum	Green Tape Aluminum	Green Tape Aluminum
EP/PI-Glass CIC,CMC	EP/PI-Glass CIC,CMC	PI-Glass Aluminum	Thick Film Aluminum	EP/PI-Glass CIC,CMC
[illegible]	PI-Glass Aluminum	[illegible]	PI-Glass Aluminum	[illegible]
PI-Glass Aluminum	[illegible]	Thick Film Aluminum	EP/PI-Glass CIC,CMC	Thick Film Aluminum

Figure 20: Ranking of Alternatives According To Measured Utility

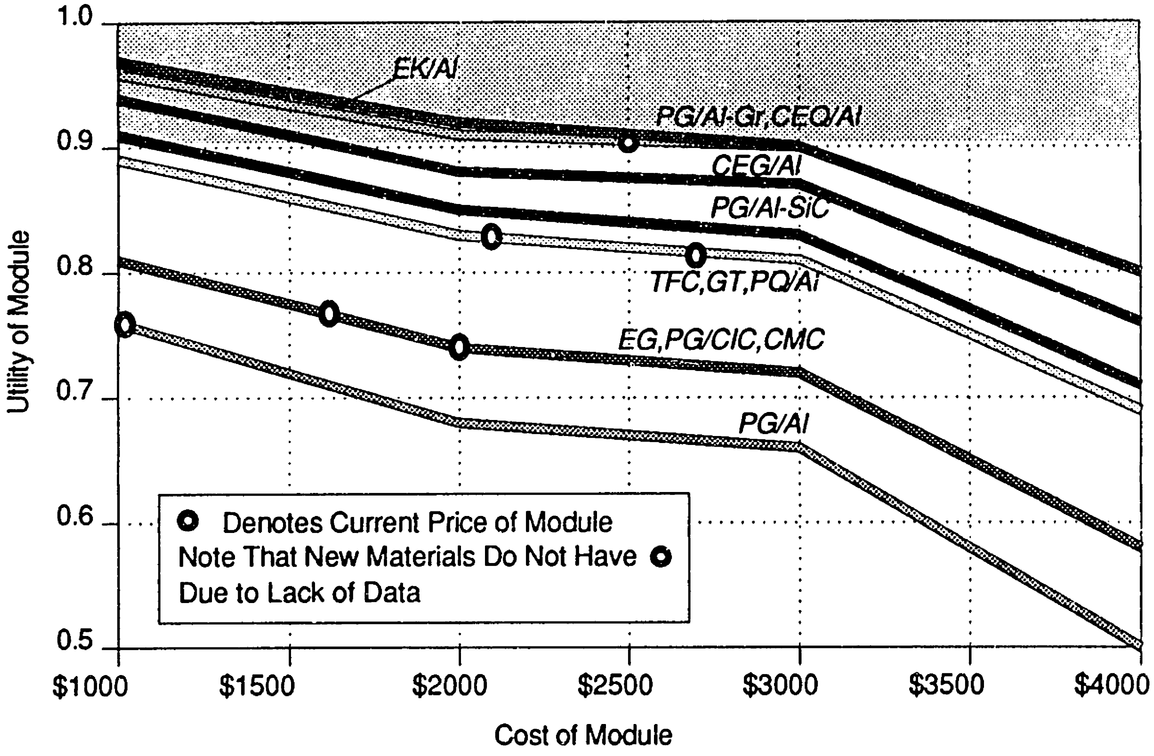


Figure 21: Effect of Cost On Utility of Module For One Interviewee

The effect of cost on the utility of the alternatives can be investigated using a plot similar to Figure 21 for each interviewees. In this plot, all the physical characteristics of the module are held constant while the cost of the module is varied. Therefore, as the cost increases, the utility decreases. Note that any alternative with a utility value higher than that of epoxy-Kevlar on aluminum, as shown in the shaded region, is more attractive. Given the current performance and price level of other alternatives, as indicated by the darkened rings, none of them is as attractive as epoxy-Kevlar on aluminum. However, new materials may become competitive with changes in performance and cost. In the next section, the implications for new materials are discussed based on all the data sets.

Implications for New Materials

Ceramic Green Tape

This analysis indicated that ceramic green tape (CGT) at its current performance level is more attractive than thick film ceramics (TFC). If, however, the dielectric constant of thick film ceramics were between 6.00 to 7.65, the two materials would be equally attractive. However, both materials are not as attractive as the Kevlar system. Of course, there are some attributes that are not taken into consideration when comparing organic and inorganic boards [69]; for example, ceramic materials have superior thermal conductivity and vibration characteristics. The high temperature stability of ceramics also improves the repairability of the substrates. If a comparison must be drawn between ceramic green tape and the organic system, the green tape system must have a dielectric constant below 4.5 for it to be as attractive as the epoxy/Kevlar systems, given its present price level. Therefore, research in ceramic green tape should focus on reducing its dielectric constant. The same can be said about thick film ceramics.

The above analysis assumes that both the thick film and green tape systems use a 40 mil alumina substrate. There are indications from manufacturers and suppliers that the fabrication of green tape ceramic board does not require the 40 mil alumina substrate; a few layers of blank tape (15-20 mils total) are sufficient to provide the required strength. In this case, the weight of the system falls to 0.5 lbs. Unfortunately, 0.5 lbs falls outside the range of the MAUA assessment and therefore, its effects cannot be evaluated. However, using a weight of 0.6 lbs for the green tape system (which would correspond to 40 mils of blank tape layers), it was found that the utility of the system increases only slightly. This improvement in utility, however, is not significant enough to raise its ranking. Therefore, the previous discussion of market implications is also applicable to the green tape system without the alumina substrate.

Cyanate Ester Systems

One of the newest materials targeted at PCB applications is the cyanate ester resin. The resin has been successfully used to produce laminates using different types of fiber, including S-glass, E-glass and quartz. Cyanate ester laminate is expected to be certified for military applications by 1990 [70]. Some of the advantages of cyanate ester laminates include a low dielectric constant, good dimensional stability, good adhesion to copper, high Tg, and possibly a price lower than that of polyimide. The manufacturing process is said to be compatible with that of FR-4 materials.

Using the currently available information for cyanate ester laminates [71] as shown in Table 30, it was found that a cyanate ester-glass (CEG) on aluminum module will be competitive at between \$1,200 and \$1,800. At a price of \$2,000 per module, the CTE must be in the range of 8 to 9 ppm/°C for CEG to be competitive. With quartz fiber, the system (CEQ) may be worth \$3,200 per module. This translates into a PCB board cost of \$310 and \$960 for CEG and CEQ respectively. The prices of CE laminates are not available now, but if they are less than the polyimide version, the above module prices for CE may actually be achievable.

Table 30: Estimated Properties of SEM "E" Module with Cyanate Ester Laminates

Module Materials	E	CTE (ppm/K)	Weight (lbs)	Cost ($)
Cyanate Ester-S glass Aluminum Heat Sink (68 mils)	3.3	9.2	0.7	****
Cyanate Ester-Quartz Aluminum Heat Sink (68 mils)	3.1	7.8	0.7	****

Through the use of the PCB cost model, the effects of the cost of the laminate and prepreg on board cost can be simulated. At present, the processing characteristics of CE are unknown, but by making assumptions regarding yield and processing parameters (as recommended by suppliers but not verified by users), it is possible to establish the effects of new material price and processing yield to achieve the target bare board price. A graph presenting the results of this analysis is presented in Figures 22 and 23.

In Figure 22, the cost of a SEM "E" board fabricated with CEG laminate is simulated using the PCB cost model. The cost of the CEG laminate is assumed to be three times the cost of the prepreg. Figure 23 shows the same plot for CEQ laminate. In this case, the cost of the laminate is taken to be twice the cost of the prepreg. The cost of a polyimide-quartz PCB is included in both plots for reference. Given the same raw material price, the polyimide version is more expensive because of its processing requirements. As the figures indicate, there is a broad band of yield and price within which cyanate ester could be a viable competitor for this application. Note that the high Tg and low dielectric constant of CE are advantages which are not accounted for in this analysis. A lower dielectric constant may allow the use of a thinner laminate, offering other advantages such as improved manufacturing yield and reduced weight.

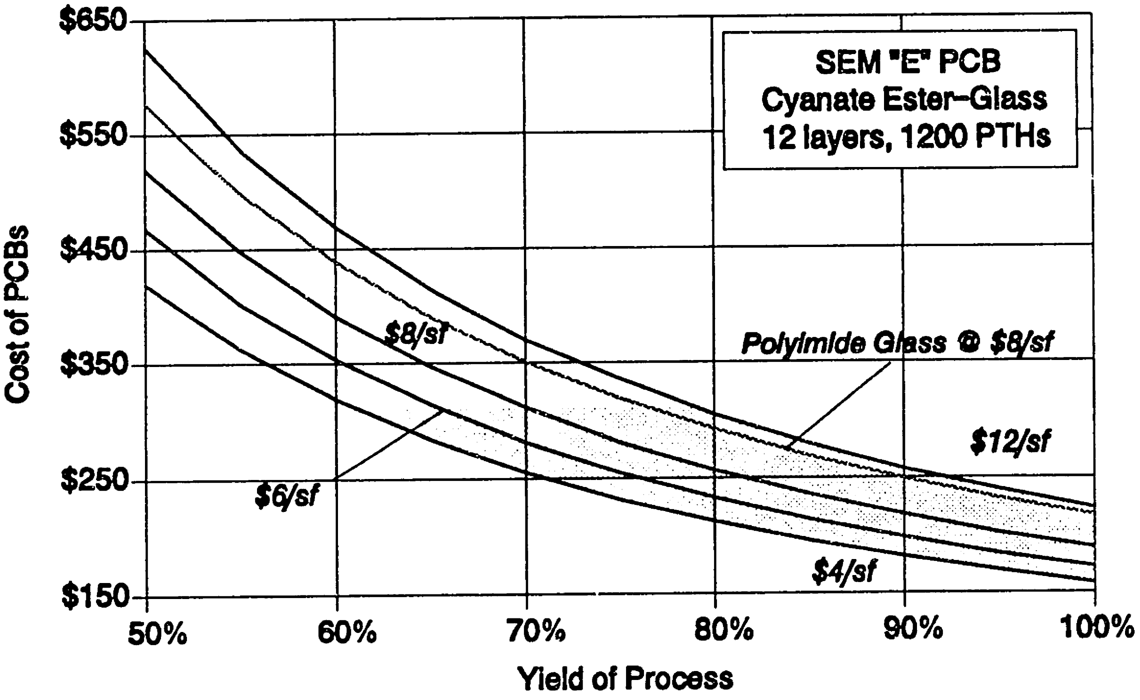


Figure 22: Effect of Yield and Raw Material Cost On CEG PCBs

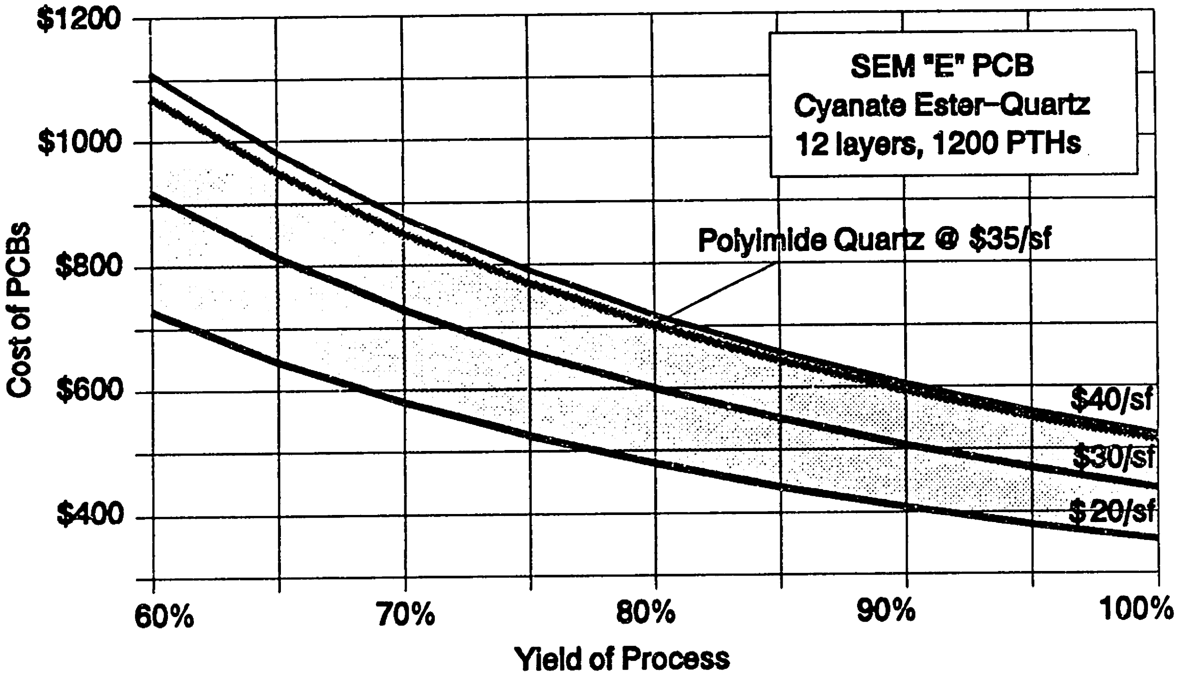


Figure 23: Effect of Yield and Raw Material Cost On CEQ PCBs

Cold Plate Materials

There has been a great deal of research work on electronics grade metal matrix composites [72,73]. Two potential materials for the SEM "E" heat sink are graphite reinforced aluminum and silicon carbide (SiC) reinforced aluminum. Table 31 list some of the physical characteristics of these composites.

Fiber reinforced aluminum offers low CTE and good thermal conductivity without the weight penalty of CIC and CMC. However, the high cost of graphite fibers raises the cost of the composite, and corrosion is a problem if the graphite fibers are exposed. SiC particulate or whisker reinforced aluminum is a lower cost material, having a higher CTE and lower thermal conductivity than Al/Gr. It does not have the galvanic corrosion problems of the Al/Gr system and could be manufactured at a much lower cost.

Assuming that these materials can be fabricated into the SEM "E" format and bonded with epoxy or polyimide-glass laminates, the estimated performance levels of the modules are tabulated in Table 32. The polyimide-glass on Al/Gr module is competitive with epoxy-Kevlar on Al if it costs less than $3,000. The improvement in thermal conductivity may also be an advantage which is not fully captured in this study. A module constructed with an Al/SiC (50% by volume) heat sink is estimated to have a CTE of 10.7 ppm/°C. Even with 55% volume SiC, the module has a relatively high CTE of 9.7 ppm/°C. Both SiC materials, when used in conjunction with polyimide-glass, are attractive only at prices below $1,200 for the module. The use of this heat sink with a low CTE laminate material, such as CEG, may be more attractive because of the lower overall CTE.

Table 31: Properties of Aluminum Based Metal Matrix Composites

Cold Plate Materials	Density (lb/si)	CTE (ppm/K)	Modulus (msi)	Heat Conductivity (W/mK)
Al/30% graphite	0.09	5.0	30	240
Al/50% SiC	0.11	9.4	25	200
Al/55% SiC	0.10	8.2	29	200

Table 32: Estimated Properties of SEM "E" Module with MMC Heat Sink

Module Materials	E	CTE (ppm/K)	Weight (lbs)	Cost ($)
Polyimide-Glass Al/30% Gr (70 mil)	4.3	7.2	0.70	****
Polyimide-Glass Al/50% SiC (70 mil)	4.3	10.7	0.73	****
Polyimide-Glass Al/55% SiC (70 Mil)	4.3	9.7	0.72	****

The earlier discussion is based on polyimide-glass on aluminum composites. Analysis of epoxy-glass on Al/Gr and Al/SiC modules produced similar results. It is expected that the price levels derived earlier are achievable with both the graphite and SiC reinforced aluminum cold plates. Both materials are available in the market in prototype quantities, but information on the processing of both materials is highly proprietary. Such information is also under Export Arms Control Act. Therefore, cost modeling technique was not used to generate cost estimates for these materials.

Summary and Conclusions

This case study is another illustration of the use of the proposed methodology to assess the potential of new materials when consideration of direct materials substitutions alone is insufficient; a systems approach must be taken and the different materials combinations that satisfy the requirements of the application must be considered. In this case, both organic and inorganic materials for the circuit board can be evaluated because the study focuses on the application requirements rather than materials performance.

The results of this analysis indicates that the epoxy-Kevlar on aluminum system is the most attractive alternative for a SEM "E" module designed to house a digital processor. However, it was also found that many new materials can be potentially competitive with slight improvements in performance. For example, if the dielectric constant of the ceramic system can be reduced below 4.5, it will become competitive with the epoxy-Kevlar system. Similarly, both polyimide-glass on Al/Gr and polyimide-glass on Al/SiC are attractive at costs below $3,000 and $1,000 respectively. Alternatively, the CTE of the polyimide-glass on Al/SiC module must be reduced to below 10 ppm/°C for it to be attractive at a cost of $2,000 per module. The new cyanate ester system will also be attractive if its price does not exceed that of the polyimide versions, and its processing characteristics are compatible with those of epoxy-glass.

Demand analysis was not applied to this case study to estimate materials demand because of the difficulty in collecting data and proprietary nature of this industry. Moreover, as demonstrated in the first case study, the demand analysis has several limitations. Therefore, it is felt that the analysis should be further refined while awaiting historical verification before it is being used to estimate demand in a highly sensitive and competitive industry.

CONCLUSIONS

Packaging and interconnection technologies have emerged as one of the critical limitations to continuing improvement in the performance, speed, and size of electronic devices. The conventional method of packaging single chips in packages and mounting them onto printed circuit boards (PCB) will prevail over the next few years because it is a mature technology compared to the newer interconnection technologies. New PCB materials will play a major role in achieving the goal of improved performance. Therefore, an understanding of the needs of the PCB industry and the prospect of new materials is crucial.

Current techniques used to evaluate the potential of new materials are the opinion survey, historical (trend) analysis and cost analysis. Each technique addresses a different aspect of the materials selection problem, but none treats all these aspects simultaneously. The objective of this study has been to develop a methodology which successfully accounts for all critical dimensions on the problem of assessing the market potential of new materials in the PCB industry.

This study has demonstrated that it is possible to devise a methodology capable of addressing the interactions among cost, performance and market effects on the market potential of new materials. The methodology consists of five stages. Engineering performance evaluation was used to define and characterize the performance of competing material alternatives. The economics of using these materials was analyzed through the development of technical cost models, which simulate the cost of manufacturing a wide range of PCB materials. Multi-attribute utility analysis was employed to evaluate how performance and cost are traded off against one another in PCB applications. These utility results were combined with an analytical framework for estimating market share as a function of time and relative utility of the alternatives. In this way, issues in cost, performance and market demand can be addressed simultaneously.

To demonstrate the power of this technique, as well as to describe and refine its application, it was used to investigate the prospect of new materials in two segments of the PCB industry: the computer and communications industry, and the military industry. Together, the two industries consume almost 80% of all domestically produced PCBs.

The application of the methodology to materials selection for computer backplanes yielded detailed and succinct information on the potential of new materials not possible with current assessment techniques. For example, the methodology enabled a quantitative assessment of the potential of cyanate ester, a materials not yet in the commercial market. Although no firm pricing has been established for cyanate ester, the methodology permits an investigation of the effects of price on the overall attractiveness of the materials through the use of the PCB cost model and the results of MAUA. The results indicate that cyanate ester has great potential in the high performance PCB market. The analysis also found that the computer industry favors high Tg materials, such as polyimide and BT, while the communications market prefers low cost materials like epoxy glass.

The second case study analyzed the materials selection problem for Standard Electronic Modules (SEM) in "E" format. Because the analysis was based on performance, rather than on specific materials or designs, it was able to compare both ceramic and organic PCBs. Two different module "designs", the constraining core and constraining dielectric construction, were also compared. Such a comparison was never made at this level of involvement; current techniques only allow comparisons within one group of materials or construction, with limited discussions on cost and performance tradeoffs.

The results of the second case study indicate that the epoxy-Kevlar on aluminum system is the most attractive alternative for a SEM "E" module designed to house a digital processor. More importantly, the technique allows a quantitative assessment of the potential of a number of newly proposed alternatives. The study results suggest that many of these alternatives can become competitive with slight improvements in performance. For example, if the dielectric constant of ceramic system can be reduced below 6.0, it will become as competitive as the epoxy-Kevlar system. Similarly, both polyimide-glass on Al/graphite and polyimide-glass on Al/SiC are attractive below $3,000 and $1,000, respectively. Again, the newly introduced cyanate ester system will be attractive if its price does not exceed that of the polyimide versions, and its processing characteristics are compatible with those of epoxy-glass.

Thus, this thesis has demonstrated the feasibility of devising a methodology capable of addressing the interactions among cost, performance and market effects on the market potential of new materials. The application of the methodology to two case studies has provided valuable insights into the respective industries. The result is a better understanding of materials and market interactions in these industries.

Recommendations for Future Work

The proposed five-stage methodology is derived from three main techniques: technical cost modeling, MAUA and demand analysis. In modeling PCB fabrication, it was found that the framework of technical cost modeling can be adapted to complex multi-step processing, but the implementation of the model in Lotus 123 spreadsheet format is limited in many aspects. Not only is the model limited by the memory capacity of Lotus, it is also very inflexible. Future work into technical cost modeling should include an investigation of "modularizing" the cost model into unit processes and linking the unit processes together according to manufacturing requirements for cost estimates.

In MAUA, the use of certainty equivalent in utility assessment is purported to eliminate the certainty bias. However, incorporating certainty equivalent into the questionnaire adds to its complexity due to the need to compare two lotteries. Work remains to be done in this area to simplify the questionnaire or develop alternative techniques to assess the utility function.

In demand analysis, which involves market and utility interactions, the lack of valid utility and market data precluded a rigorous study on the framework. Therefore, the use of the analysis in the first case study is limited in many respects. It would be valuable to apply the framework to cases involving direct demand (not derived demand) to further refine the framework in future work. However, data limitations remain a critical problem when making market evaluations.

This thesis has presented a technique for evaluating material competitiveness in a single level of packaging. Although the methodology captures the important issues of cost, performance and market interactions in assessing the prospects of new materials for PCBs, it does not address the competition between alternative packaging technologies. For example, is an optimized single chip packaging system on highly complex PCBs a "better" alternative than an optimized multichip packaging system on less complex PCBs? This class of questions suggests that, ultimately, the problem of materials selection in electronics packaging cannot be resolved by looking at any single packaging level, but must be evaluated on the basis of the total system. Extending the methodology presented here to this assessment should provide similar insights into the competitiveness and future opportunities for alternative packaging strategies.

APPENDIX A

Multi-Attribute Utility Analysis Questionnaire

Materials for Computer Backplanes

Introduction

This questionnaire is designed to explore, briefly but quantitatively, your preferences for different characteristics of materials. We are aware that it is limited in several ways and we hope you will feel free to comment on the content. The procedures implicit in this questionnaire have been validated in theory and in practice, but their use in this form is *experimental*.

In particular, the questionnaire is a preliminary exploration of the factors leading to the selection of a material for a particular application. We recognize that the purview of this questionnaire is limited and we encourage you to comment and advise us of any apparent limitations.

The purpose of this questionnaire is *not* to model the decision-making *environment*, but rather to provide insight into how you, the decision-maker, view the necessary trade-offs associated with materials selection for this particular application. It is designed to help us understand your expert professional judgment. As such, **there are no right or wrong answers** to questions. Rather, through your answers to these questions, we hope to learn how you tradeoff the different characteristics of materials that are relevant to the application.

We recognize that by expressing engineering decision problems in this way, we are asking you to react to an artificial situation which may be very unfamiliar and unrealistic to you. However, please bear with us and answer the questions as thoroughly as you can.

Technical Note

The quantification of the intensity of your preferences is based upon specific questions regarding your preference between pairs of uncertain situations. There are two (and only two) possible outcomes to each lottery: the first lottery involves one outcome (A) with probability **p**, where **p** is less than 1; and a second outcome (B) with the complementary probability **1-p**. The second lottery similarly contains two outcomes (C) and (D), with a 50% probability of each occurring. Graphically, the uncertain situation is shown as:

Frequently, engineers confronted with this type of questions would immediately want to use paper and pencil to calculate the expected value of the two lotteries and to select their answers accordingly. However, such analyses may not form the basis for actual decisions, both inside and outside of the engineering sphere. Other factors enter into enter into this decision (what decision analysts call "attitute towards risk"). For example, the success of state lotteries relies upon the fact that people will choose to take chances even when the odds are not in their favor. Alternatively, insurance companies stay in business because there are people who will not not take chances, even when the odds are in their favor.

Engineering decisions are colored by similar sorts of attitudes towards risk and it is these sorts of attitudes that we are trying to assess. You should feel free to use a calculator to compute your answers if you really do make all of your material decisions on that basis. Otherwise, we urge you to base your answers upon how you actually do make decisions, rather than how you believe they ought to be made.

***** PRACTICE *****

Practice Scenario

At this point, it is instructive to go through a practice example that is illustrative of the MAUA process. Suppose that we were interested in examining how you view the trade off between your annual income and your weekly free time. The questions would be posed as follows.

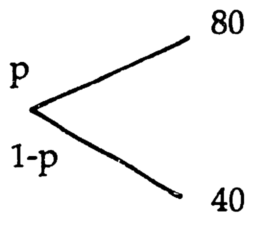
SALARY

Suppose you currently have a job, but that you are offered a new position within the same company. The new position pays $60,000 per year, but your manager suggests that there is a 50% chance that your salary would soon increase to $80,000 per year at this new position. However, a 50% chance remains that you will always earn $60,000 per year at this new job.

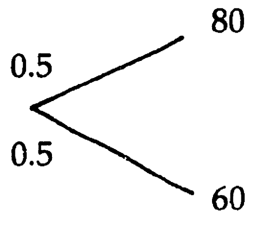
Your other possible choice is to retain your current position which pays $40,000 per year. You believe that there is a probability **p** that you will get a raise elevating your annual salary to $80,000. The probability **1-p** remains that you will always be paid $40,000 per year at your current job.

Would you keep your current job if the probability **p** were:

At what probability **p** would you be indifferent to keeping your current job and taking the new job?



Current Job



New Job

***** PRACTICE *****

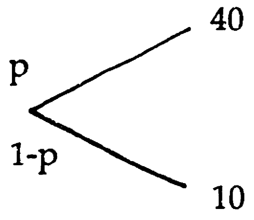
FREE TIME

Your current position allows for only 10 hrs/wk free time. You believe that there is a probability **p** that an assistant will be hired for you, lightening your workload and resulting in 40 hrs/wk free time for you. The probability **1-p** remains that no one will be hired, and you will always have 10 hrs/wk free time.

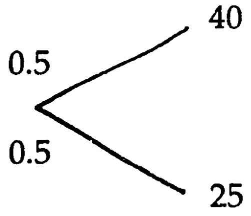
Suppose that you are offered a new position within the same company. The two positions pay the same. The new position allows for 25 hrs/wk of free time, but your manager suggests that there is a 50% chance that once you become familiar with the new job your free time will increase to 40 hrs/wk. However, a 50% chance remains that you will always have only 25 hrs/wk of free time at this new job.

Would you keep your current job if the probability **p** were:

At what probability **p** would you be indifferent to keeping your current job and taking the new job?



Current Job

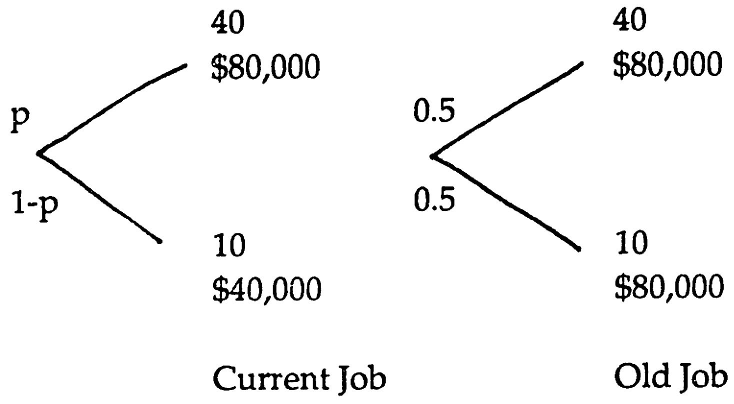


New Job

***** PRACTICE *****

You currently hold a position that pays $40,000 per year and allows for 10 hrs/wk of free time. However, you believe that there is a probability **p** that you will soon get a raise to $80,000 per year, and that an assistant will be hired to help you, leaving you with 40 hrs/wk of free time. A probability **1-p** remains that neither of these occurances will happen leaving you at your situation.

Suppose you are offered a new position at the same company that pays $80,000 per year, but still only allows for 10 hrs/wk of free time. Your manager, however, suggests that there is a 50% chance that you will soon become familiar with this new position, allowing you to accomplish your work more quickly and leaving you with 40 hrs/wk of free time. A 50% chance remains that familiarity with this new job does not result in any increase in free time. Would you keep your current position if the probability **p** were:

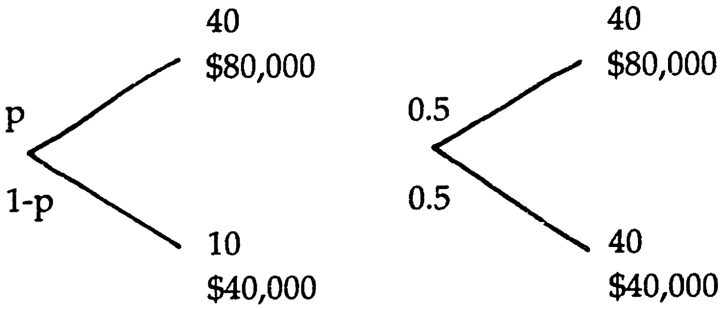


At what probability **p** would you be indifferent to keeping your current job and taking the new job?

***** PRACTICE *****

You currently hold a position that pays $40,000 per year and allows for 10 hrs/wk of free time. However, you believe that there is a probability **p** that you will soon get a raise to $80,000 per year, and that an assistant will be hired to help you, leaving you with 40 hrs/wk of free time. A probability **1-p** remains that neither of these occurances will happen leaving you at your situation.

Suppose you are offered a new position at the same company that still pays $40,000 per year, but allows for 40 hrs/wk of free time. Your manager, however, suggests that there is a 50% chance that, based on your performance in this new position, you will get a raise elevating your annual income to $80,000. A 50% chance remains that your performance in this new position is not good enough to warrent a raise and you always make $40,000. Would you keep your current position if the probability **p** were:



Current Job New Job

At what probability **p** would you be indifferent to keeping your current job and taking the new job?

****

Now that you have had some exposure to the methodology to be used, let's proceed to the actual questionnaire.

Materials for Backplanes

I have selected several characteristics of laminates which I believe are taken into consideration when choosing a material for the backplane to be used in the design shown in Figure 1. The characteristics are listed below, along with the set of units for these characteristics and their best and worst values.

Characteristic	Units	Best	Worst
Dielectric Constant		2.2	4.6
CTE (z-axis,25-125oC)	ppm/C	40	60
Cost	$	500	4500
Others			

Like so much of this questionnaire, this list is a preliminary one. I am very interested in your opinion of its content. If you think that some of the listed characteristics are irrelevant to the decision, please indicate so above. Additionally, if there are characteristics which you believe should be included, please add them to the list.

Questionnaire Structure

This questionnaire is directed toward an engineer or manager involved with the design of computer backplanes. It is especially intended for an engineer involved with determining the engineering performance criteria used to make materials selection decisions concerning the backplane.

The questionnaire is based on the following fabricated scenario. Consider yourself to be the engineer responsible for developing the backplane to be used in your company's next generation of computer. The intended design is shown in Figure 1. This *design* is fixed although the *materials* from which it is to be constructed are not.

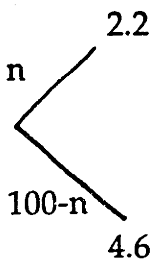
It is the beginning of the project, and you must decide very soon on which materials to use in the backplanes. Based on the performance specification given to you (such as noise budget, reliability etc.) you have determined that the current material cannot be used. There are many materials available in the market now and you have to decide which one to use. There is a new class of laminates called LAMX which appear to be very promising. Due to the unfamiliarity of the engineers with the new LAMX materials, there are variations in the performance of the prototypes produced.

At your request, your engineers have presented some initial data to aid your decision. In all cases, assume that their evaluation is correct and accurate. I will present scenarios which ask that you make a materials selection decision based on these data. The questionaire consists of two parts: the first part contains questions on only one attributes while the second parts involves all the attributes. Your responses to these questions suggest how you trade-off the pertinent materials attributes. If the questions are ambiguous to you, please discuss it with the interviewer.

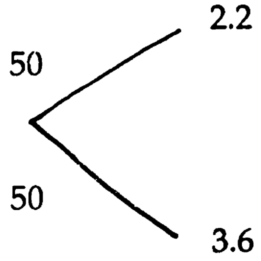
PART I

DIELECTRIC CONSTANT

The engineers in your project believe that a backplane made with either of two new, recently developed materials, **LAMX-1** and **LAMX-2**, will perform exactly the same, EXCEPT for the dielectric constant. 100 prototypes using each materials were built and tested. Out of the 100 specimens using **LAMX-1**, 50 were found to have a dielectric constant of only 2.2 while the remaining 50 exibit a dielectric constant of 3.4. On the other hand, there are "n" number of prototypes built with **LAMX-2** which has a dielectric constant of 2.2 and (100-n) with dielectric constant of 4.6.



LAMX-2



LAMX-1

Would you prefer to use **LAMX-2 or LAMX-1** if the n were:

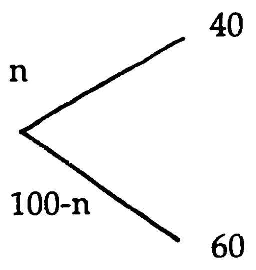
n 90 60

y/n

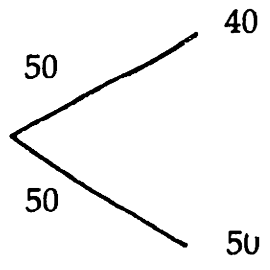
At what n would you be indifferent to the use of **LAMX-1** or **LAMX-2** in the backplane?

COEFFICIENT OF THERMAL EXPANSION (CTE)

The materials engineers has been evaluating two new, recently developed materials, **LAMX-5** and **LAMX-6**. It was found that both perform exactly the same, EXCEPT for the CTE (z-axis,25-125^{o}C). Out of the 100 tests performed on **LAMX-3**, 50 were found to have an average CTE of 40 ppm/ C while the remaining 50 exhibit CTE of 50. On the other hand, there are "n" number of prototypes built with **LAMX-4** which has a CTE (z-axis,25-125oC) of 40 C and (100-n) with an average CTE of 60^{o}C.



LAMX-4



LAMX-3

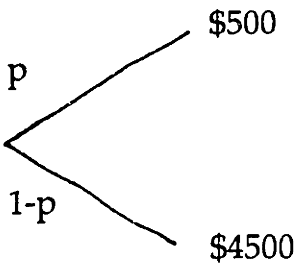
Would you prefer to use **LAMX-3 or LAMX-4** if the n were:

n	90	60
y/n		

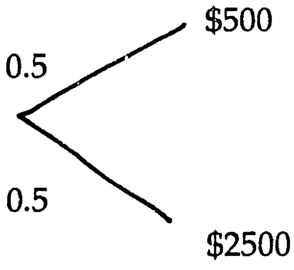
At what n would you be indifferent to the use of **LAMX-3** or **LAMX-4** in the backplane?

COST

The manufacturing engineers has been evaluating the cost of making backplanes using two new, recently developed materials, **LAMX-5** and **LAMX-6**. It was found that the performance characteristics of the finished backplanes were exactly the same. However, the cost associated with **LAMX-6** ere found to have a 50/50 chance of being $500 or $2500. On the other hand, there is a probability "p" that the cost of a bare backplane built with **LAMX-6** is $500 and a complementary probability of (1-p) that it will be $4500.



LAMX-5



LAMX-6

Would you prefer to use **LAMX-5 or LAMX-6** if the probability p were:

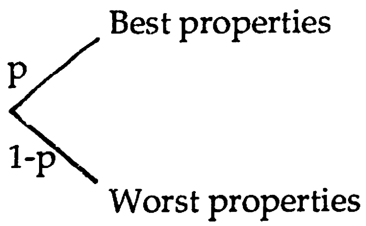
n 0.9 0.6

y/n

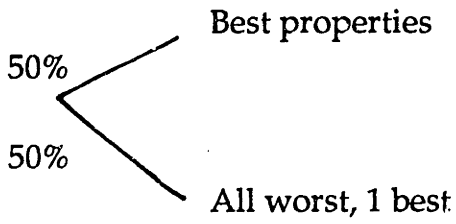
At what p would you be indifferent to the use of **LAMX-5** or **LAMX-6** in the backplane?

PART II

The following set of questions asks you to choose between using a new material **LAMX** and another new material **LAMX-AVE**. There exists a 50% chance of upgrading the material **LAMX** to the dream material with all of the best properties, and a probability p of doing the same with the **LAMX-AVE** material. However, there is also a 50 % chance that **LAMX-AVE** will become the material with the worst possible properties with unproper processing. Similarly, the properties of **LAMX** may be degraded during processing such that it has all of the worst properties, EXCEPT one attribute which is at its best level. It is up to you to decide which of these materials to use based on the magnitude of this probability **p**.



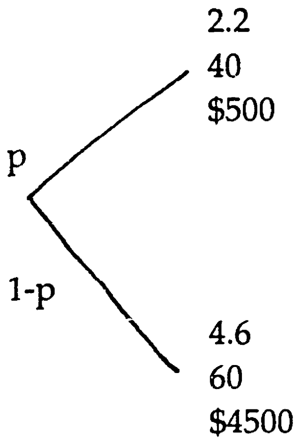
LAMX-AVE



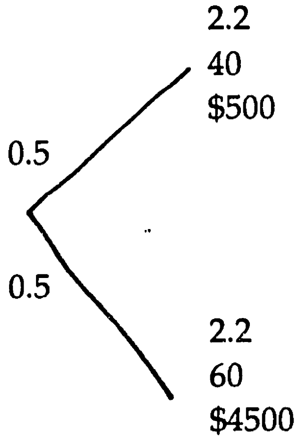
LAMX

DIELECTRIC CONSTANT

Currently, **LAMX-AVE** is available. Your engineers believe that it has great potential. In fact, they think that there is a probability **p** that, with some processing ingenuity, it could become the dream material possessing all of the best performance characteristics. But there is also a probability **1-p** that processing will degrade this material such that it have the worst possible properties. You have another material, **LAMX-A**, with a very low dielectric constant, but with otherwise extremely poor properties. There is a 50% chance that its properties could be improved to those of the dream material through careful processing, and an equal chance that its properties will not be altered.



LAMX-AVE



LAMX-A

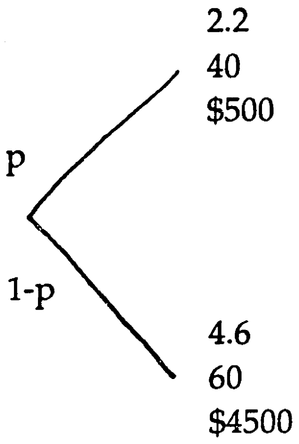
With no further information available in the near future, would you prefer to use **LAMX-AVE** over **LAMX-A** if the probability **p** were:

p 0.9 0.64

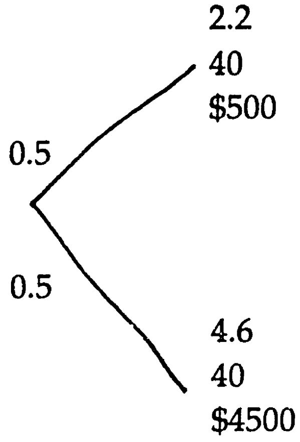
what probability **p** would you be indifferent to the use of **LAMX-A** to **LAMX-AVE** as the backplane material?

COEFFICIENT OF THERMAL EXPANSION (CTE)

Again, **LAMX-AVE** is available. Your engineers believe that there is a probability **p** that, with some processing ingenuity, it could become the dream material possessing all of the best performance characteristics. But there is also a probability **1-p** that processing will degrade this material such that it have the worst possible properties. You have another material, **LAMX-D**, with a very high CTE (z-axis,25-125oC), but with otherwise extremely poor properties. There is a 50% chance that its properties could be improved to those of the dream material through careful curing, and an equal chance that its properties will not be altered.



LAMX-AVE



LAMX-D

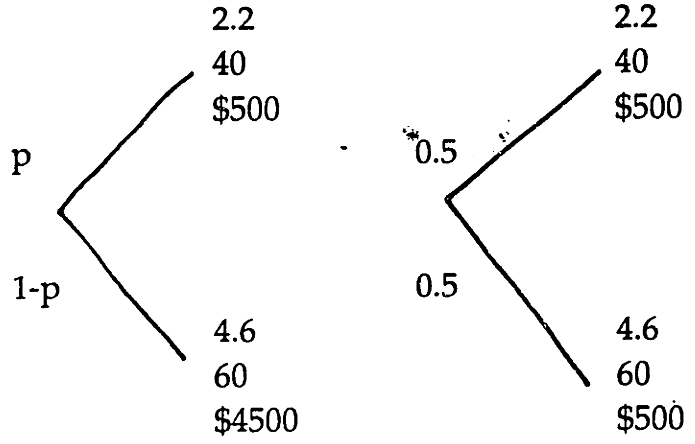
With no further information available in the near future, would you prefer to use **LAMX-AVE** over **LAMX-B** if the probability **p** were:

p 0.9 0.8

At what probability **p** would you be indifferent to the use of **LAMX-B** to **LAMX-AVE** as the backplane material?

COST

Again, two materials **LAMX-AVE** and **LAMX-C** are available. **LAMX-AVE** has the worst possible physical properties but is very cheap. However, there Your engineers believe that there is a probability **p** that, with some processing ingenuity, it could become the dream material possessing all of the best performance characteristics. But there is also a probability **1-p** that processing will not improve its properties. In that case, you would have to incur extra cost to rework the backplane. Similarly, **LAMX-AVE** has extremely poor physical properties but that it is very cheap. There is a 50% chance that its properties could be improved to those of the dream material through careful processing at no extra cost, and an equal chance that its properties will not be altered.



LAMX-AVE **LAMX-C**

With no further information available in the near future, would you prefer **LAMX-AVE** to **LAMX-D** if the probability **p** were:

p 0.9 0.6

At what probability **p** would you be indifferent to the use of **LAMX-D** to **LAMX-AVE** as the backplane material?

-- end --

APPENDIX B

Multi-Attribute Utility Analysis Questionnaire

Materials for SEM "E" Modules

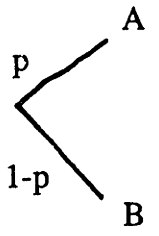
Introduction

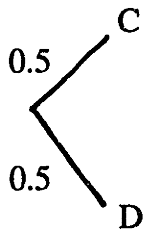
This questionnaire is designed to explore, briefly but quantitatively, your preferences for different characteristics of materials. We are aware that it is limited in several ways and we hope you will feel free to comment on the content. The procedures implicit in this questionnaire have been validated in theory and in practice, but their use in this form is *experimental.* In particular, the questionnaire is a preliminary exploration of the factors leading to the selection of a material for a particular application. We recognize that the purview of this questionnaire is limited and we encourage you to comment and advise us of any apparent limitations.

The purpose of this questionnaire is ***not*** to model the decision-making *environment*, but rather to provide insight into how you, the decision-maker, view the necessary trade-offs associated with materials selection for this particular application. It is designed to help us understand your expert professional judgment. As such, **there are no right or wrong answers** to questions. Rather, through your answers to these questions, we hope to learn how you tradeoff the different characteristics of materials that are relevant to the application.

Technical Note

The quantification of the intensity of your preferences is based upon specific questions regarding your preference between pairs of uncertain situations. There are two (and only two) possible outcomes to each lottery: the first lottery involves one outcome (A) with probability **p**, where **p** is less than 1; and a second outcome (B) with the complementary probability **1-p**. The second lottery similarly contains two outcomes (C) and (D), with a 50% probability of each occurring. Graphically, the uncertain situation is shown as:





Frequently, engineers confronted with this type of questions would immediately want to calculate the expected value of the two lotteries and to select their answers accordingly. However, such analyses may not form the basis for actual decisions, both inside and outside of the engineering sphere. Other factors enter into enter into this decision (what decision analysts call "attitute towards risk"). For example, the success of state lotteries relies upon the fact that people will choose to take chances even when the odds are against them. Alternatively, insurance companies stay in business because there are people who will not take chances, even when the odds are in their favor.

Engineering decisions are colored by similar sorts of attitudes towards risk and it is these sorts of attitudes that we are trying to assess. You should feel free to use a calculator to compute your answers if you really do make all of your material decisions on that basis. Otherwise, we urge you to base your answers upon how you actually do make decisions, rather than how you believe they ought to be made.

Materials for Standard Electronic Modules

The attached figure shows a SEM "E" module which will be used as the basis of this case study. The module will be used to house a digital processor for the next generations of avionics equipment for airplanes (or even satellites). The processor may run at more than 100 Mhz to produce up to 5 mips. This study will focus on the materials for the substrate, which could be organic or inorganic, and the cold plate. However, the cold plate and the substrate will not treated separately in this study; rather, the entire module will be considered as an entity which optimized materials and designs combination.

Given the performance requirement of this module, please answer the following questions using your expert judgement regarding the appropiate components packaging and module design:

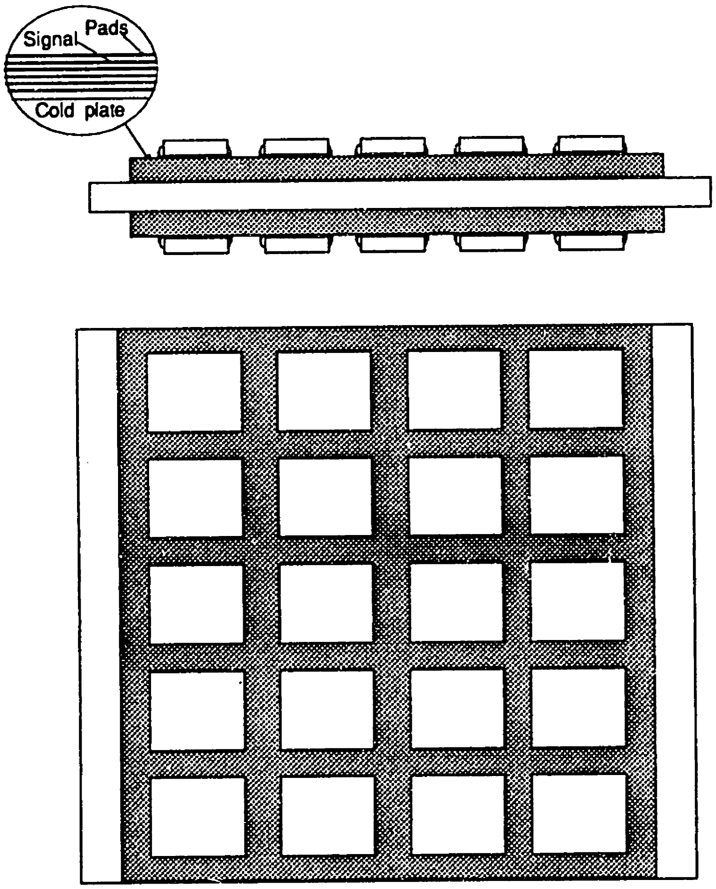
Components Used:	Leaded chip carriers Leadless chip carriers Pin Grid Array Chip on Board
Substrates Used:	Ceramics Epoxy/Kelvar Epoxy/Glass Polyimide/Glass Polyimide/Quartz PTFE
Cold Plate:	Low CTE (CMC, CIC, AL/B) Aluminum Copper

I have selected several characteristics of CTE controlled substrate which I believe are taken into consideration when choosing a material for the module described. The characteristics are listed below, along with the set of units for these characteristics and their best and worst values.

Attribute	Units	Minimum	Maximum
Dielectric Constant		3	8
CTE (x-y)	ppm/°C	7	12
Weight	lbs	0.6	1.2
Cost ($)	$	1000	4000
Others			

Like so much of this questionnaire, this list is a preliminary one. I am very interested in your opinion of its content.

Typical Module for Military Avionics



PRACTICE

At this point, it is instructive to go through a practice example that is illustrative of the MAUA process. Let's deviate from Standard Electronic Modules and talk about your perspectives on a new job. Suppose that we were interested in examining how you view the trade off between your annual income and your vacation time. The questions would be posed as follows.

SALARY

Suppose you currently have a job, but that you are offered a new position within the same company. Both positions pay $50,000 per year, but your manager at the new job suggests that there is a 30% chance that you will get a raise elevating your annual salary to $80,000. Your other possible choice is to retain your current position which pays $50,000 per year. You believe that there is 50% chance that you will get a raise elevating your annual salary to $60,000. Given this situation, which job do you prefer?

Current Situation	50% likelihood	Future Option A
$50,000	-------------->	$60,000

-- OR --

Current Situation	30% likelihood	Future Option B
$50,000	------------>	$80,000

At what percent likelihood would you be indifferent to keeping your current job and taking the new job?

PRACTICE

VACATION

Your current position allows for only 14 vacation days. You believe that there is a 50 % chance that a change in company policy will result in an increase of vacation days to 18 for you.

Suppose that you are offered a new position within the same company. The two positions pay the same. The new position allows for 14 vacation days, but your manager suggests that there is a 30% chance that your vacation days will increase to 21 if you can tranfer your seniority from your previous position. Given this situation, which job would you prefer?

Current Situation	50% likelihood	Future Option A
14 days	------------->	18 days

-- OR --

Current Situation	30% likelihood	Future Option B
14 days	------------->	21 days

At what percent likelihood would you be indifferent to keeping your current job and taking the new job?

PRACTICE

SALARY

You currently hold a position that pays $50,000 per year and allows for 14 vacation days. However, you believe that there is a 50% chance that you will soon get a raise to $80,000 per year. A 50% chance remains that it will not happen, leaving you at your current situation.

Suppose you are offered a new position at the same company that pays $50,000 per year and allows for 14 vacation days. Your manager, however, suggests that there is a 30% chance that you will soon become familiar with this new position, allowing you to be promoted to an executive position paying $80,000 with 21 vacation days. Would you keep your current position give this situation?

Current Situation	50% likelihood	Future Option A
$50,000		$80,000
14 days	------------>	14 days

-- OR --

Current Situation	30% likelihood	Future Option B
$50,000		$80,000
14 days	------------>	21 days

At what percent likelihood would you be indifferent to keeping your current job and taking the new job?

PRACTICE

VACATION

You currently hold a position that pays $50,000 per year and allows for 14 vacation days. However, you believe that there is a 50% chance that you will soon get 21 days of vacation per year due to company reorganization. A 50% chance remains that it will not happen, leaving you at your current situation.

Suppose you are offered a new position at the same company that pays $50,000 per year and allows for 14 vacation days. Your manager, however, suggests that there is a probability **p** that you will soon become familiar with this new position, allowing you to be promoted to an executive position paying $80,000 with 21 vacation days. A probability **1-p** remains that familiarity with this new job does not result in any promotion.

Current Situation	50% likelihood	Future Option A
14 days	------------->	21 days
$50,000		$50,000

-- OR --

Current Situation	30% likelihood	Future Option B
14 days	------------->	21 days
$50,000		$80,000

At what percent likelihood would you be indifferent to keeping your current job and taking the new job?

****

Now that you have had some exposure to the methodology to be used, let's proceed to the actual questionnaire.

Questionnaire Structure

This questionnaire is directed toward an engineer or manager involved with the selection of materials for Standard Electronic Modules. It is especially intended for an engineer involved with determining the engineering performance criteria used to make materials selection decisions concerning the substrates.

The questionnaire is based on the following fabricated scenario. Consider yourself to be the engineer responsible for developing the substrate to be used in your company's next generation of avionics equipment. The intended design is shown in the attached figure. This *design* is fixed although the *materials* from which it is to be constructed are not.

It is the beginning of the project, and you have been given funding for developing the materials for the modules. The following set of questions asks you to choose between a materials research program **PROX-A** and another program **PROX-B**. Program A has 50% chance of success but the payoff is quite low, i.e., the results of the program will only yield a material with slight improvement in one material properties. Of course, a 50% chance exist that the program will not yield any improvement in any material properties. On the other hand, program B promises a probability **p** of improving one properties of the material to the best possible level. It is up to you to decide which of these programs to commit your limited research funding based on the magnitude of this probability **p**.

The questionnaire consists of two parts: the first part contains questions on only one attributes while the second parts involves all the attributes. If the questions are ambiguous to you, please discuss it with the interviewer.

PART I

DIELECTRIC CONSTANT

The materials engineers have been evaluating the dielectric constant of two new dielectric materials, **MATX-A** and **MATX-B**. Currently, both materials has a dielectric constant of 10, which is unacceptable for the digital processor you are designing. Based on the preliminary tests data, you were told that there is a 50% chance of reducing the dielectric constant of MATX-A to 6 through research and development. On the other hand, there is also a 30% chance of reducing the dielectric constant of MATX-B to 3.0 through research and development.

Current Situation	50% likelihood	Future Option A
8 Units	------------->	6 Units

-- OR --

Current Situation	30% likelihood	Future Option B
8 Units	-------------->	3 Units

Based on this information and your assessment of the needs of your module, which material would you prefer to commit your development funding?

At what probability of the success of option B would you be indifferent to the two options?

COEFFICIENT OF THERMAL EXPANSION (XY)

The systems engineers have been evaluating the CTE (xy) of two new module constructions, **MODX-A** and **MODX-B**. Currently, both modules has a CTE (xy) of 14 ppm/°C, which is unacceptable for the digital processor you are designing. Based on the preliminary tests data, you were told that there is a 50% chance of reducing the CTE (xy) of MODX-A to 10. On the other hand, there is also a 30% chance of reducing the CTE (xy) of MODX-B to 6 through research and development.

Current Situation	50% likelihood	Future Option A
12 ppm/°C	------------->	10 ppm/°C

-- OR --

Current Situation	30% likelihood	Future Option B
12 ppm/°C	-------------->	7 ppm/°C

Based on the given information, which module construction would you prefer?

WEIGHT OF MODULE

The systems engineers have been evaluating the weight of two new module constructions, **MODX-A** and **MODX-B**. Currently, both materials has a weight of 1.4 lbs, which is maximum allowable weight for the digital processor you are designing (the specifications actually called for a weight of 1.0 lbs). Based on the preliminary tests data, you were told that there is a 50% chance of reducing the weight of MODX-A to 1.0 through. On the other hand, there is also a 30% chance of reducing the weight of MODX-B to 0.6 through research and development. Note that any reduction of weight can be used to carry payloads and is therfore beneficial.

Current Situation	50% likelihood	Future Option A
1.4 lbs	------------->	1.0 lbs

-- OR --

Current Situation	30% likelihood	Future Option B
1.4 lbs	-------------->	0.6 lbs

Given this information, which module construction would you prefer?

COST

The manufacturing engineers have been evaluating the cost of making the modules using two new, recently developed processes, **PROX-A** and **PROX-B**. It was found that the performance characteristics of the finished substrates were exactly the same. Currently, both modules cost $4000 to fabricate. PROX-A has a 50% chance of reducing the cost to $2000. On the other hand, there is another new process PROX-B which has a 30% chance of reducing the cost to $500.

Current Situation	50% likelihood	Future Option A
$4000	------------->	$2000

-- OR --

Current Situation	30% likelihood	Future Option B
$4000	-------------->	$500

Which process would you prefer?

PART II

The following set of questions asks you to choose between a materials research program **PROX-A** and another program **PROX-B**. Program A has 50% chance of success but the payoff is quite low, i.e., the results of the program will only yield a material with improvement in only one material properties. Of course, a 50% chance exist that the program will not yield any improvement in any material properties. On the other hand, program B promises a probability **p** of developing the dream material with all of the best properties. It is up to you to decide which of these programs to commit your limited research funding based on the magnitude of this probability **p**.

Current Situation	50% likelihood	Future Option A
Worst	------------->	All Worst, 1 Best
	(Low Payoff Program)	

-- OR --

Current Situation	p% likelihood	Future Option B
Worst	-------------->	Best
	(High Payoff Program)	

DIELECTRIC CONSTANT

You have been allocated the funding for a research program for improving the materials for Standard Electronic Modules. Two program options are available. Program A has a 50% chance of success, but the results of the program will yield a material with improvement only in the dielectric constant; other material properties will remain at the worst levels. Of course, a 50% chance exists that the program will not yield any improvement in dielectric properties, leaving you with a material with all its worst properties. On the other hand, program B promises a probability **p** of upgrading the research material to the dream material with all of the best properties. A complementary probability of **(1-p)** exists that the research will fail to make any improvement to the material, leaving you with a material with all its properties at its worst levels.

Current Situation		Future Option A
10 Units		3 Units (Best)
14 ppm/°C	50% likelihood	14 ppm/°C
1.4 lbs	------------->	1.4 lbs
$4000		$4000

(Low Payoff Program)

--- OR ---

Current Situation		Future Option A
10 Units		3 Units
14 ppm/°C	p% likelihood	6 ppm/°C
1.4 lbs	------------->	0.6 lbs
$4000		$500

(High Payoff Program)

With no further information available in the near future, would you prefer to commit to program **A** over program **B** if the probability **p** were:

p 30% 40% 20%

At what probability **p** would you be indifferent to the programs?

COST

Two research program options are available. Program A will focus mainly on the manufacturing cost and has a 50% chance of success. The results of program A will yield a low cost material with poor material properties. Of course, a 50% chance exist that the program will not yield any reduction in cost. On the other hand, program B promises a probability **p** of upgrading the research material to the dream material with all of the best properties at minimum cost. A complementary probability of **(1-p)** exists that the research fail to do any improvement to the material, leaving you with an expensive material with properties at its worst levels.

Current Situation		Future Option A
10 Units		10 Units
14 ppm/°C	50% likelihood	14 ppm/°C
1.4 lbs	------------->	1.4 lbs
$4000		$500 (Best)

(Low Payoff Program)

--- OR ---

Current Situation		Future Option A
10 Units		3 Units
14 ppm/°C	p% likelihood	6 ppm/°C
1.4 lbs	------------->	0.6 lbs
$4000		$500

(High Payoff Program)

With no further information available in the near future, would you prefer to commit to program **A** over program **B** if the probability **p** were:

p	30%	40%	20%

At what probability **p** would you be indifferent to the programs?

PART III: DIRECT TRADEOFFS

The following set of questions asks you to trade off cost directly for improvement in materials properties. The baseline module construction will be assumed to have the following levels of performance.

Current Substrate Attributes:

Cost : ________
Weight : _______ lbs
CTE (xy) : _____ ppm/°C
Dielectric Constant : ______
Cold Plate Material : ______
Cold Plate Thickness : ______ mils

Suppose you currently have a material with a dielectric constant of 4.5. How much would you pay for an otherwise identical module with a dielectric constant of:

3 _____ 5 _____ 6 _____ 8 _____

Suppose you currently have a module with a CTE (xy) of 12 ppm/°C. How much would you pay for an otherwise identical module with a CTE (xy) of:

10 _____ 8 _____ 7 _____ 6 _____

Suppose you currently have a module which weighs 1.0 lbs. How much would you pay for an otherwise identical module weighing:

1.2 _____ 1.1 _____ 0.8 _____ 0.6 _____

---- End ----

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