Multi-Attribute Utility Analysis: Applications in Materials Selection and Market Analysis

Richard de Neufville, Joel Clark, and Frank R. Field

Materials Selection Problem

- **Given:**
  - **Set of Materials with Properties N**
  - **Engineering Application with Performance Objectives M**
- **What is the “best” material for the application; or**
  Which material will be chosen for that application?
- **Not just Engineering Design Problem**

Materials Selection Problem (contd)

- **Also, the heart of**
  - **Materials Research and Development**
  - **Strategic Positioning**
  - **Market Development and Pricing**
  - **Material Substitution Analysis**

Classical Materials Selection Techniques

- **Engineering**
  - **Sorting Techniques**
  - **Indexing Techniques**
- **Economic**
  - **Regression/Statistical Techniques**

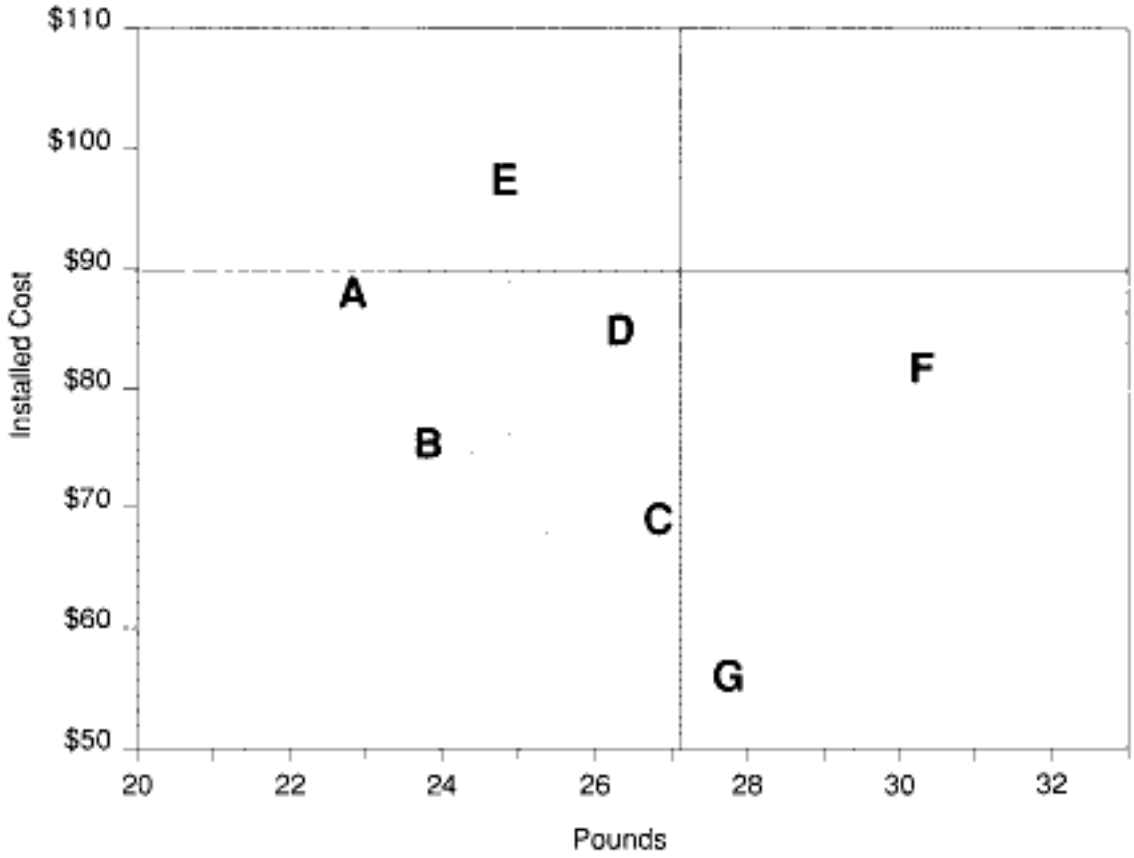
Engineering Technique - Sorting

- Most Commonly Used Technique
- Easy to Understand and Implement
- Process:
  - Establish minimum acceptable performance targets
  - Throw out all materials not meeting those targets
  - Order the remaining techniques by one dimension (usually cost)
  - Use the lowest cost alternative

Engineering Technique - Sorting (contd)

- **Disadvantages**
  - **Simplistic View of Materials Selection**
  - **Unable to Capture Trade-off Behavior**

Engineering Technique - Sorting



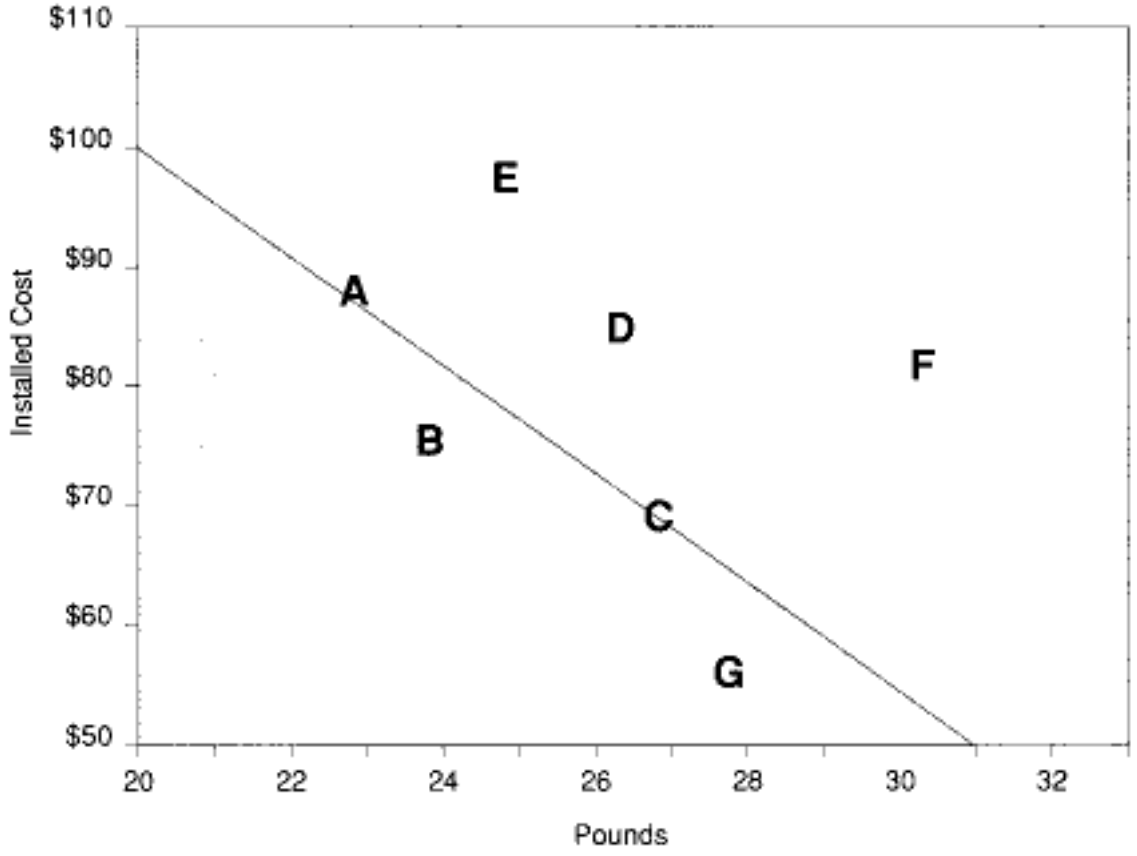
Engineering Technique - Indexing

- **Becoming More Commonplace with Advent of Computer Tools**
- **Bases Material Selection on Weighted Average of Relevant Characteristics**

$$\text{Index} = \Sigma A_i X_i / X_i^*$$

- **Difficulties with Indexing**
  - **What does the index mean?**
  - **How does one define the weightings?**
  - **Normalization**

Engineering Technique - Indexing



Normalization of Indexes

Insidious Problem -

Choice of Normalization Constants

Changes the Relative Rankings

Alternatives	Cost	Density
A	50	11
B	60	9
C	80	7
D	120	10

$$\text{INDEX} = \frac{0.5\ \text{Cost}}{\text{Cost}^*} + \frac{0.5\ \text{Density}}{\text{Density}^*}$$

Normalization of Indexes (contd)

Normalizing Factors	Relative Value of Index
$Cost_A$, $Density_A$	A<B<C<D
$Cost_B$, $Density_B$	B<A<C<D
$Cost_C$, $Density_C$	C<B<A<D
$Cost_D$, $Density_D$	C<B<A<D
AVG (All Cost & Density)	B<A<C<D
MIN (All Cost & Density)	B<C<A<D
MAX (All Cost & Density)	C<B<A<D
MAX (All Cost & Density but D)	B<A<C

Economic Technique - Hedonic Pricing

- **Normative Technique:**
  - **Regresses Price against Characteristics**
  - **Resulting Coefficients are "Value" of a Unit of Characteristic**
- **Weaknesses:**
  - **Difficult to Incorporate Engineering Features**
  - **Difficult to Treat More Than Two Materials at a Time**
  - **Primary Characteristics Treated are Prices; Not Engineering Performance (Price Index Analysis**
  - **Like All Regression Techniques, Implicitly Assumes That the Future Will be Same as the Past**

Alternative Approach - Utility Analysis

- Decision Analysis Tool
- Developed to Treat Multi-Objective Problems
- Treats Multi-dimension Comparisons
- Yields Quantitative Measure via Analytic Transformation
  - Quantitative Rankings
  - Tradeoff Character of Decision Process
- Replicates Decision-making - Based on Revealed Preferences

Utility Analysis

- Takes Explicit Consideration of Decision-maker Preferences
- Measures Preference Structure, Rather Than Imposing One
- Firm Theoretical Basis - Disciplined Assessment of Decision Process
- Yields Quantitaive Measure of Relative Value of Alternatives

Steps of Multi-Attribute Utility Analysis

- Identify Critical Performance Parameters
- Develop Interview Questionnaire
- Administer Questionnaire
- Develop Utility Function
- Analyze results

Possible Applications of Multi-Attribute Utility Function

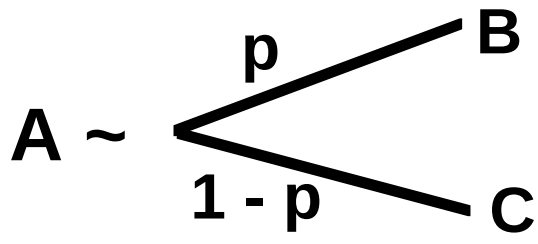
- Material Ranking against Alternatives
- Materials Performance Limitations/ Advantages
- Advantages/Disadvantages of Strategic Changes

Value of Multi-Attribute Utility Approach

- Treats Performance Characteristics, Not Material Characteristics
- Identifies Material Advantages/ Disadvantages
- Quantifies Degree of Performance Advantage/Disadvantage
- Suitable for Strategic Analysis, Price Setting, R&D Allocation

Utility Assessment - Interview Process

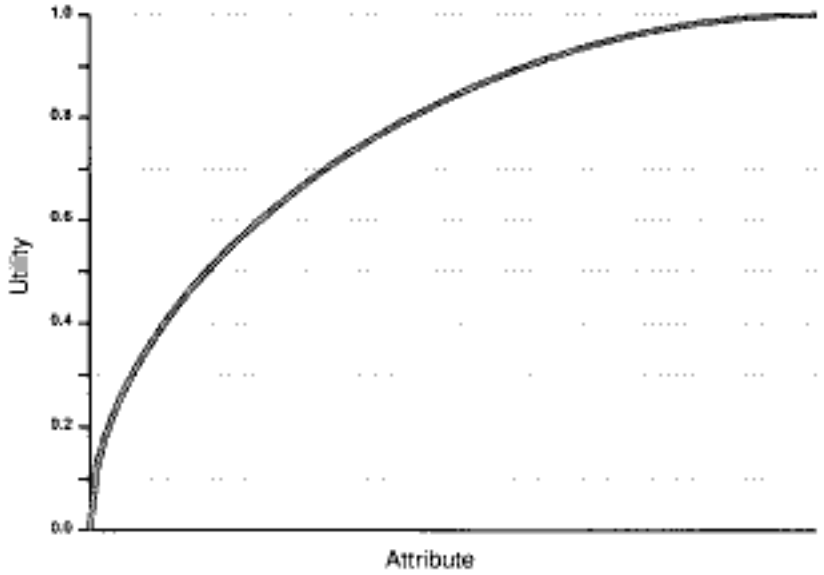
- **Development of Sophisticated Questionnaire**
- **Indirectly Addresses Measurement of Individual Preferences**
- **Performed through the Presentation of Uncertain Situations**
- **Situations Presented to Match, Wherever Possible, Realistic Decision Situations**



Interview Data ⟶ Utility Function

- **Single Attribute Utility Function**
- **Relates Levels of Attributes to Preferences**
- **Directly Measured during Interview**

Typical Utility Curve



Utility Function - Continued

- **Single Attribute Utility Functions are Combined to Form Multi-Attribute Utility Functions**

  2-Dimensional Utility Function

  $$U(x,y) = Kk_xk_yU(x)U(y) + k_xU(x) + k_yU(y)$$

  N-Dimensional Utility Function

  $$KU(X) + 1 = \pi(Kk_iU(x_i) + 1)$$

- **k_i's are Determined During Interview**
- **Functional Form Based upon Assumptions Validated during Interview**
- **K is a Dependent Scaling Factor**

Case Studies in Utility Analysis

- Bumpers
- Resin Pricing
- Electronic Materials - Power Module Stackup
- PCB Laminates

Bumper Case Study

- New Polymer/Designs Developed for Bumper Systems
- Questions:
  - How Does the Cost of the New Systems Compare with Current Systems?
  - Are the New Systems Competitive?
  - If Not, What Could be Done to Make Them Competitive?
  - If So, What are the Particular Strengths of the New Systems?

Bumper Case Study (contd)

- **Methodology:**
  - **Estimate Manufacturing Costs with MSL Cost Models**
  - **Use Multi-Attribute Utility Analysis To:**
    - **Identify Competitive Position of New Systems**
    - **Define Strengths and Weaknesses, and**
    - **Suggest Development Strategies**

Performance Characterisitics of Interest

- Developed through Literature Reviews, Engineering Considerations, and Industry Contacts

Characteristics for Utility Analysis

Deflection Distance Service Life Dent Resistance

Cost FMVSS Performance Weight

- Others Treated as "Binary"
  - Minimum Acceptable Levels of Performance
  - No Additional Value to Performance beyond Minimum Standard
- Performance Characteristics Are:
  - Material Blind and Consequence of Physical Parameters of Materials and Design

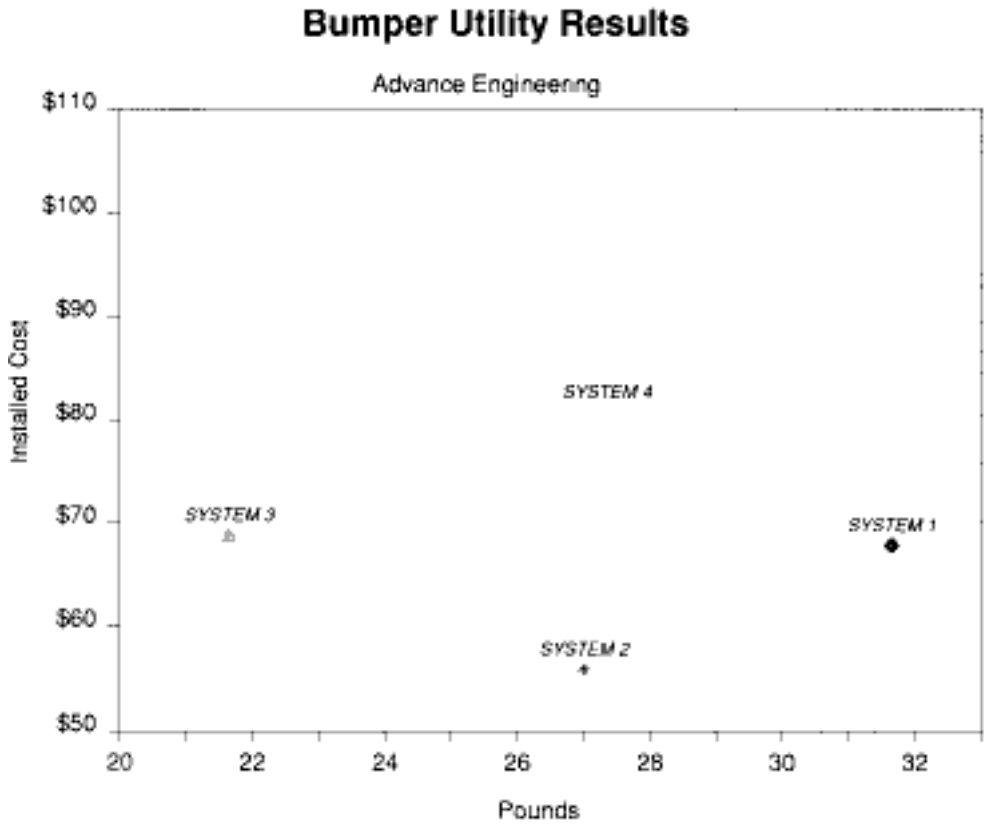
Utility Interview/Questionnaire

- **Materials Acceptance Situations Presented**
- **Subject Asked to Respond to Given Situation:**
  Material is available which may give better performance than the current materials, but may yield worse. What must the probability of getting better performance be before you will accept the uncertain material?
- **Administered to Advance Engineering - Bumpers**
- **Also Administered to Purchasing**

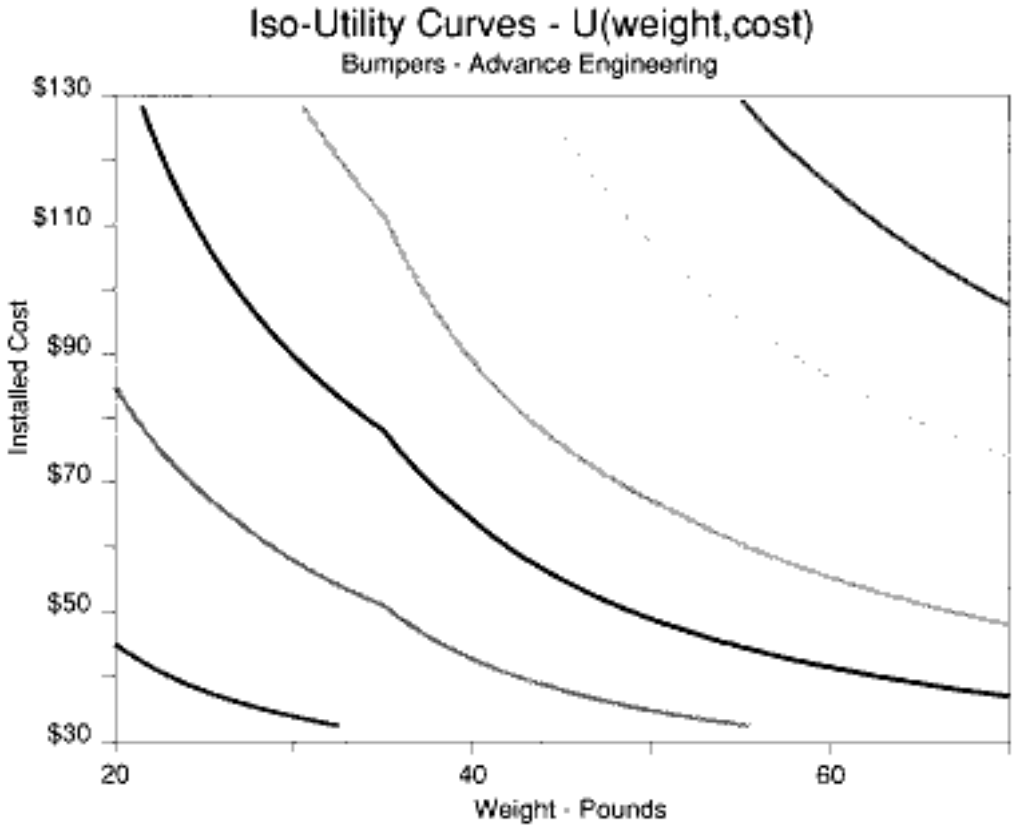
Qualitative Results

- **Cost and Weight are Only Characteristics Traded-off**
- **Other Four Characteristics Binary:**
  - **FMVSS Differences a Consequence of Company Policy**
  - **Service Life Increases of Value Only if Entire Car Matches the Bumper**
  - **Dent Resistance and Deflection Distance Engineering "Bogeys"**
- **In Purchasing, Cost Only Characteristic of Interest**

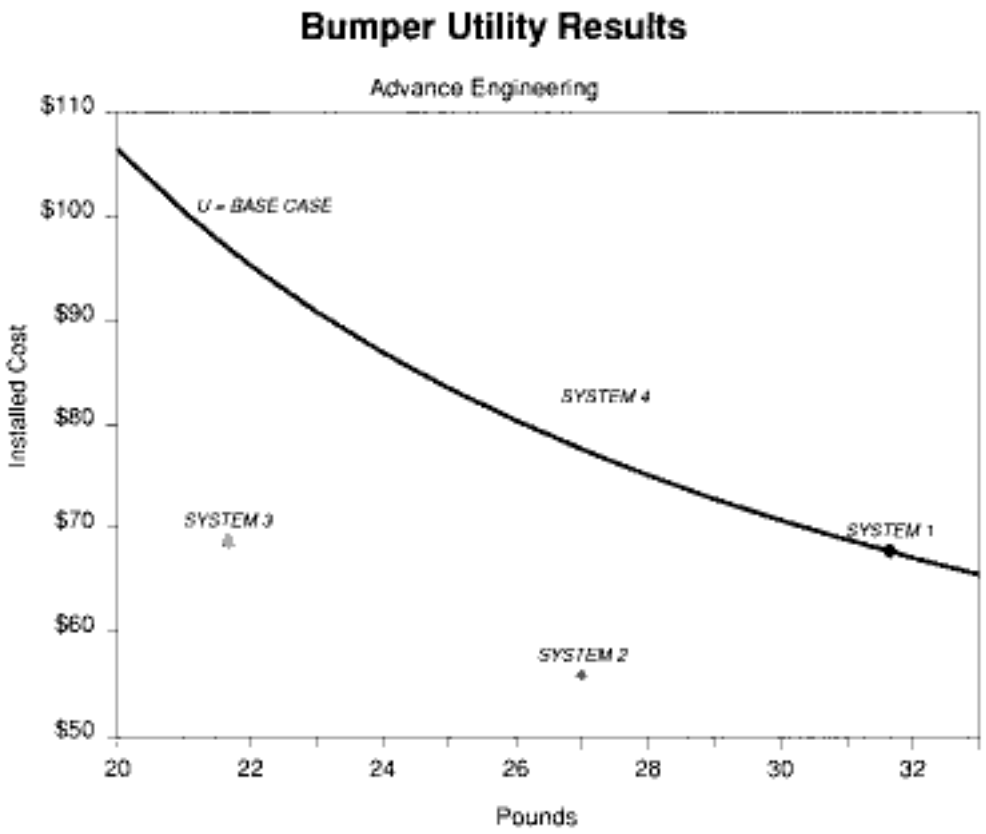
Bumper Case Alternatives



Utility Results - Bumper Case



Utility Results - Bumper Case



Bumper Case Conclusions

- **System 3 Had Substantial Advantage over Base Case, Although System 2 Was Comparable**
- **System 4 Was Not Competitive As Currently Developed, Cost and Weight Too High**

Potential for Use	
System 3:	**Competitive Now**
System 4:	**Not Competitive Now**
Possible Strategies:	**Eliminate EAU's**
	Reduce Wall Thickness
	Reduce Resin Price

Resin Pricing Case

- Resin with Better Processibility
- Question: How to Position New Resin?
- Specific Strategies to Evaluate:
  - Increase/Decrease Resin Price
  - Increase Technical Support

Characteristic Evaluation

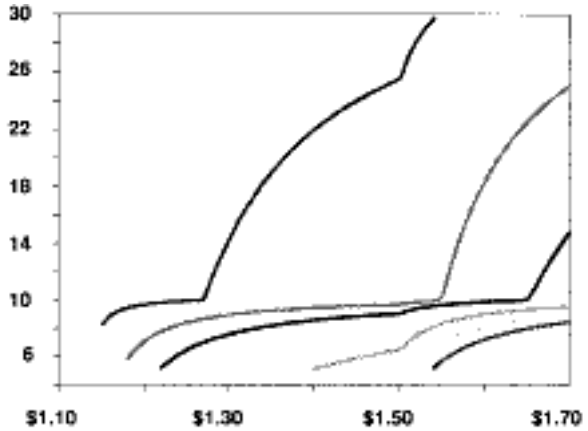
- **Well Defined Distinctions between Current Resin, New Resin, and Competing Resins**
- **Utility Questionnaire Developed around Material Acceptance Again**
- **Performance Characteristics**

Cost	**Quality of Technical Support**
Processibility	**Physical Characteristic of Resin**

Focus of Utility Analysis

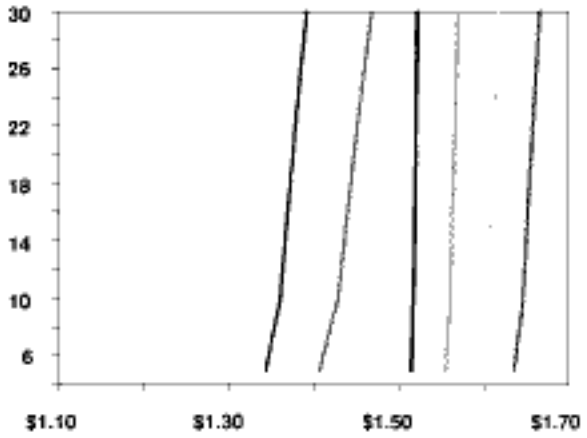
- **Distinctions between Classes of Consumers**
  - **Independent Molders**
  - **Captive Molders**
  - **Large Part Molders**
  - **Small Part Molders**
  - **End-users**
- **Processing Characteristic of Interest Only to Molders, Not to End-users**
- **Physical Performance Characteristic Purely Binary**
- **Cost Relatively Insensitive**

Molder vs End-User Utilities



Molder Utility Function Slope of Curves Indicates a Willingness to Pay for Better Processibility

End-User Utility Function Vertical Curves Indicate That Cost is the Only Performance Feature of Interest



Results - Resin Pricing Case

- **Slopes of Utility Curves, Combined with Classical Econometric Techniques, Indicated That Price Elasticity of Demand for the Resin Was Small**
- **Improvements in Processibility Were of Value to Molders**
- **Increase Technical Support Perceived as Valuable**

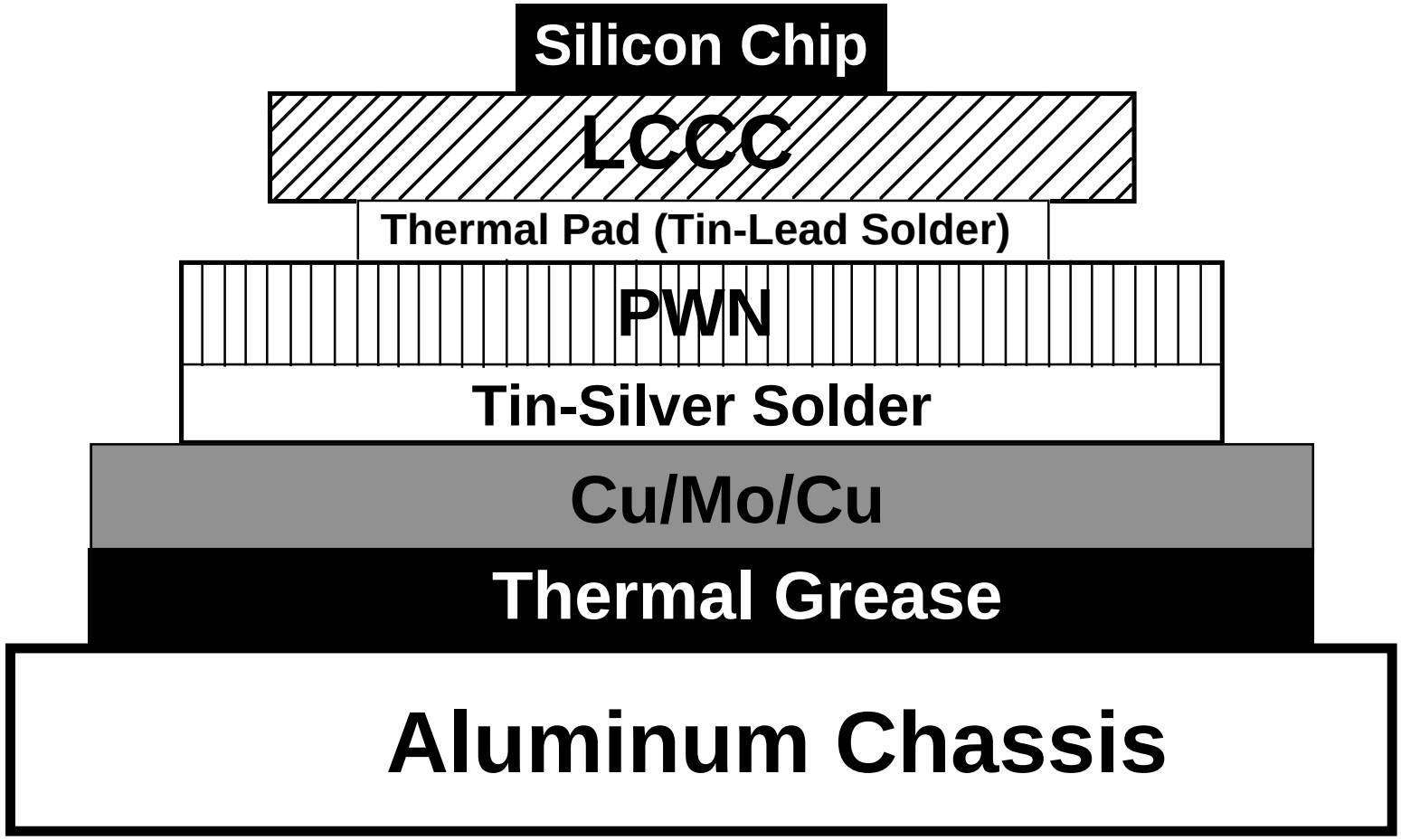
Results - Resin Pricing Case (contd)

- **Recommendations**
  - **If New Producers Will Price Compete - Offer New Resin at Same Price as Old Resin**
  - **If New Producers Will Not Price Compete - Offer New Resin at Increased Price**
  - **Under No Condition Offer Resin at Reduced Price**

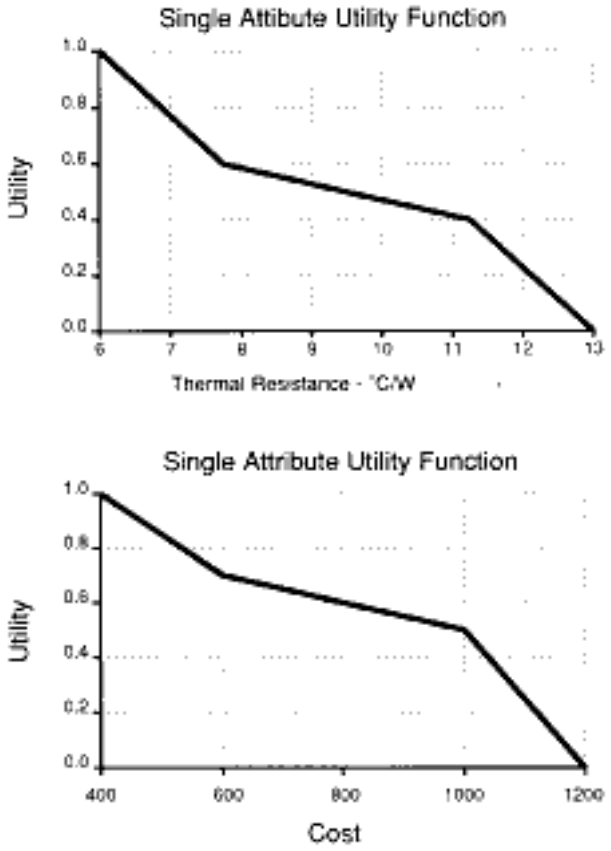
Electronic Application - Power Module

- Military Avionics Power Module
- Thermal and Manufacturing Limitations Due to Materials in System
- Question:
  - What Materials Can Yield Better Thermal Performance?
  - Which Materials Offer the Best Value in This Use?
- Bulk of Work Developed Feasibility and Costs of Alternatives
- Utility Analysis Employed to Identify Which of the Alternatives Would be Worthwhile to Pursue

Simplified Drawing of Stackup

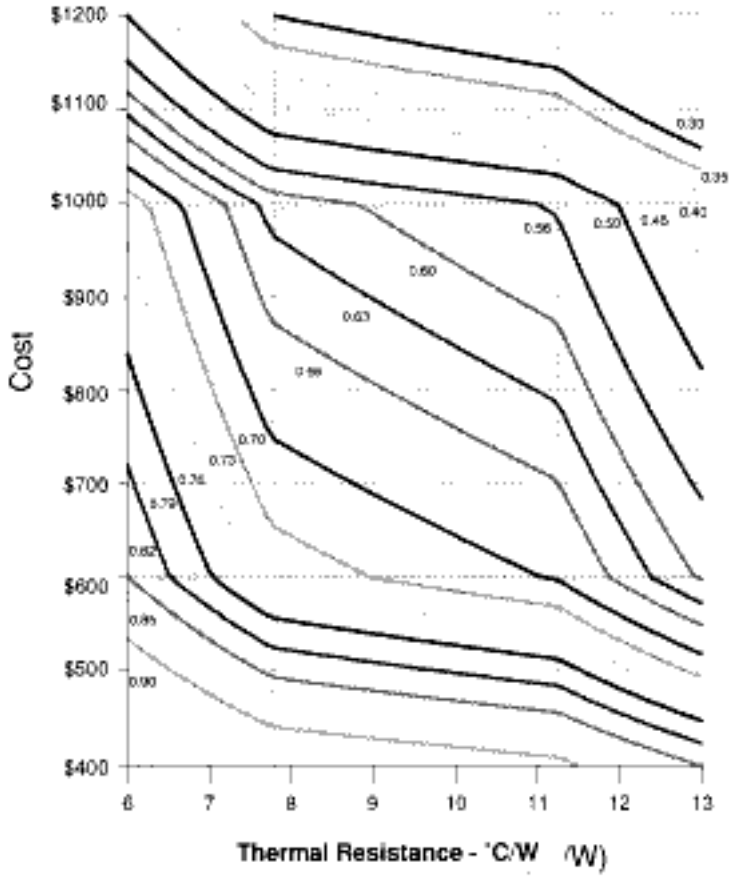


Single Attribute Utility Functions

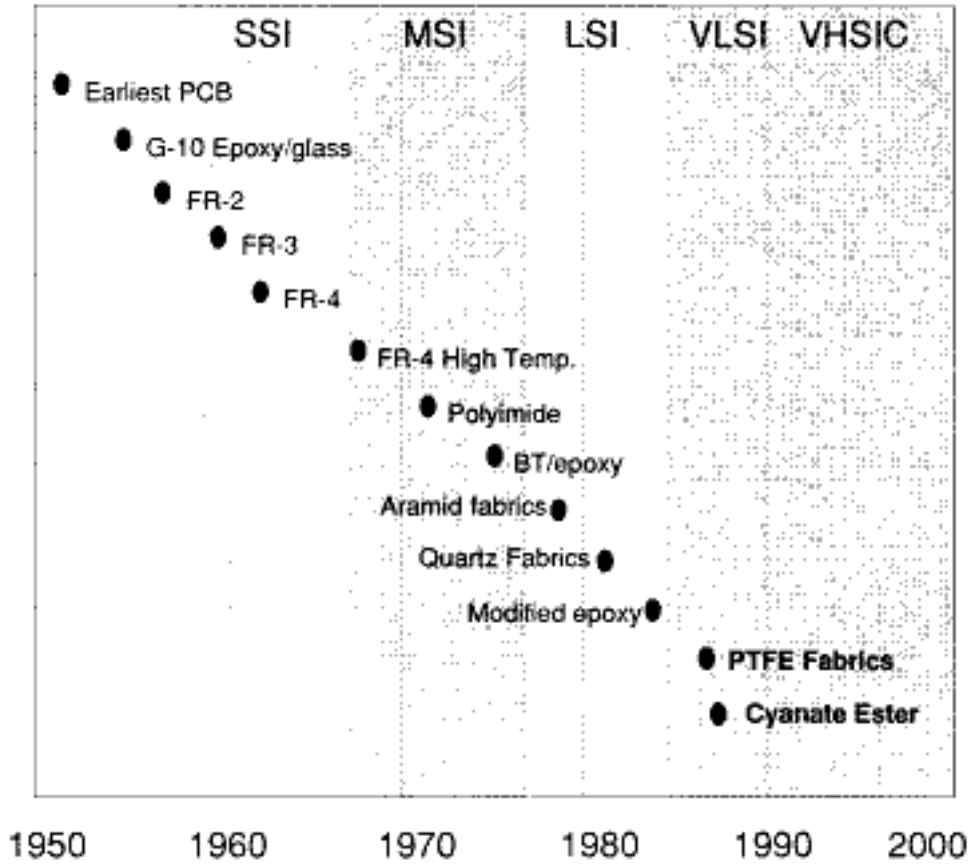


Both Functions Have a Broad Middle Range over Which Utility Varies Little, and End Ranges Where Utility Changes Sharply

Multi-Attribute Utility Map



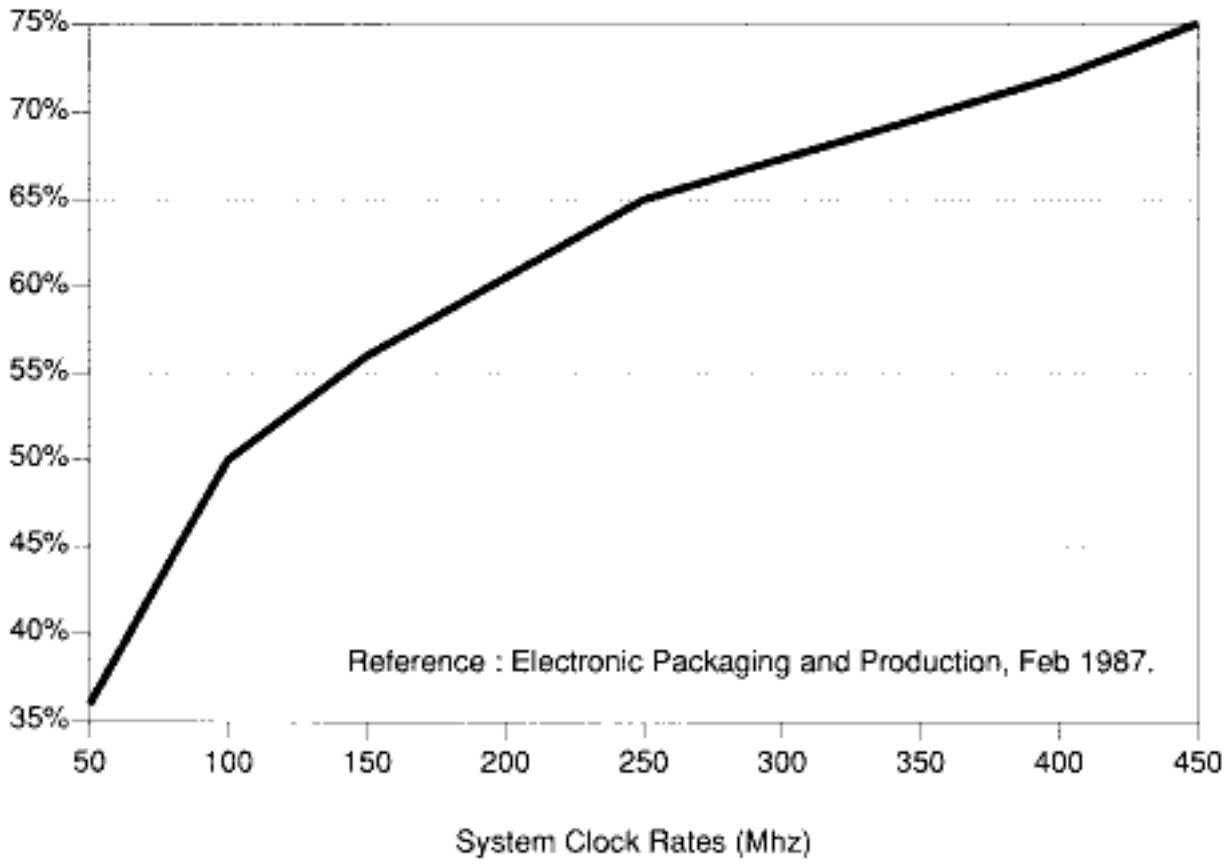
PCB Laminates - Historical Trends



Need for New Materials

- **Electronic Circuitry More Densely Packed Thus, Fabrication of Fine Lines/Multiple Layers Critical Also, Electrical Properties Influence System Performance**
- **Devices Becoming More Powerful and Faster Therefore Hotter; Heat Dissipation Critical Design Element**
- **$$$ - Cost Competition**

Influence of Package on System Performance

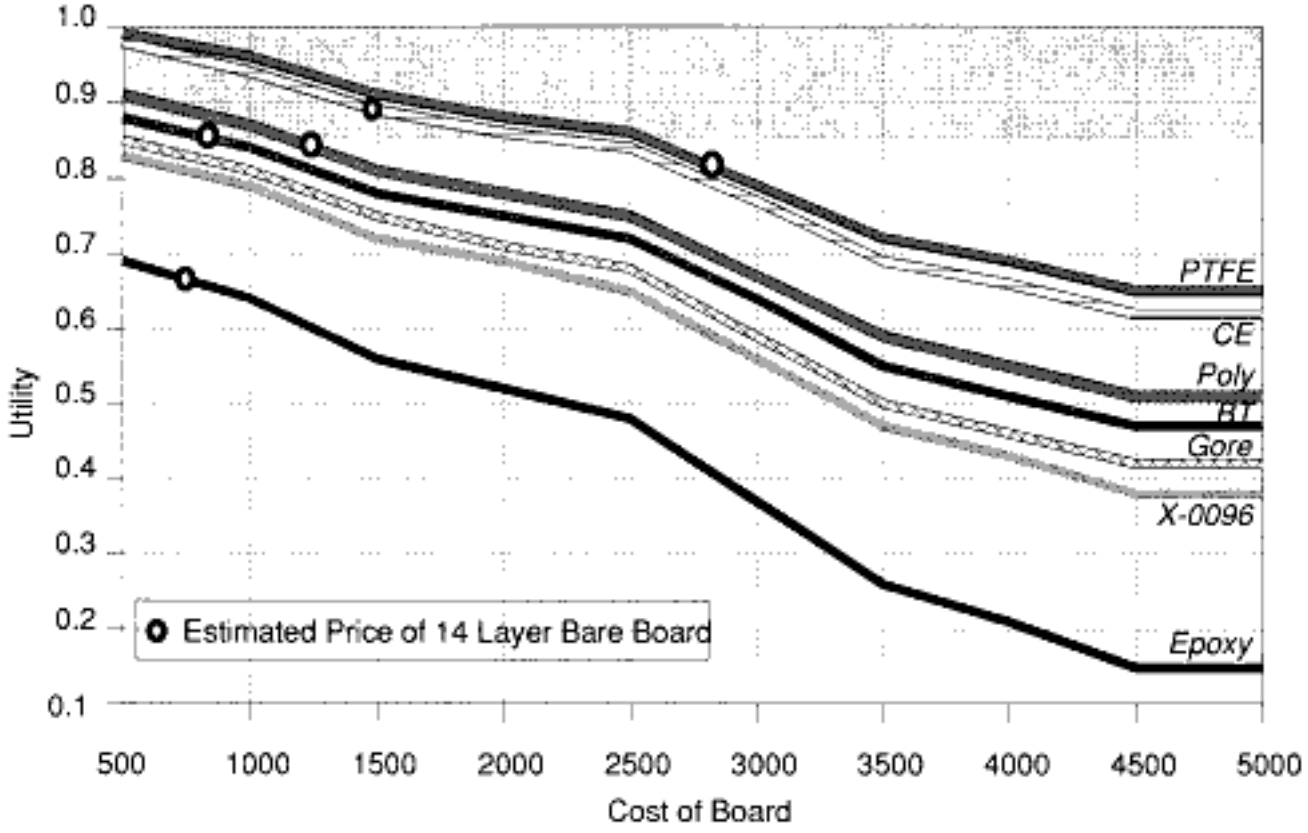


Examination of Materials for PCBs

- Critical Performance Characteristics
- Influence Upon Demand
- Competitiveness of Current and Prospective Materials
- Critical Performance Attributes
  - Dielectric Constant — System Delay
  - Glass Transition Temperature — CTE; other thermal perf.
  - Cost — Market Driver

Utility Analysis Used to Evaluate Material Alternatives in Several Markets; Telecommunications & Computers

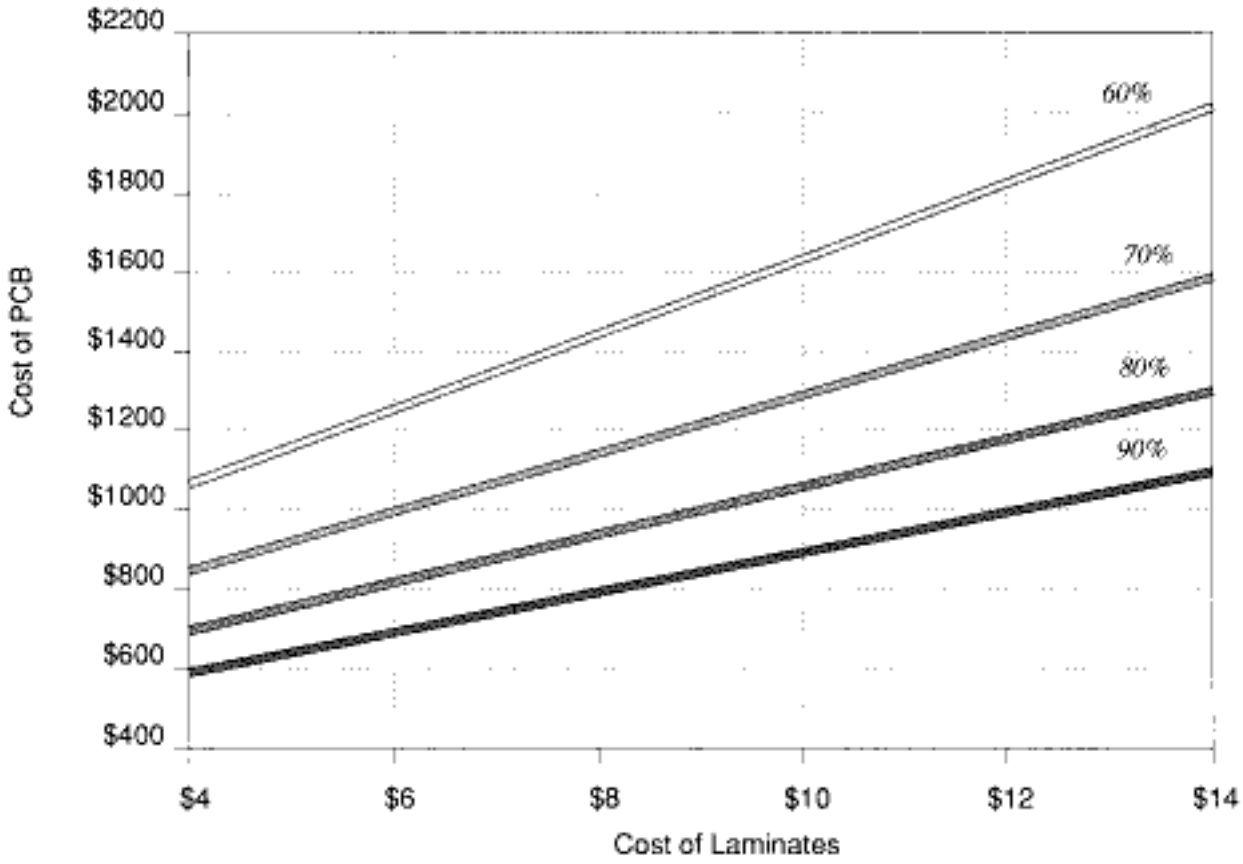
MAUA Rankings



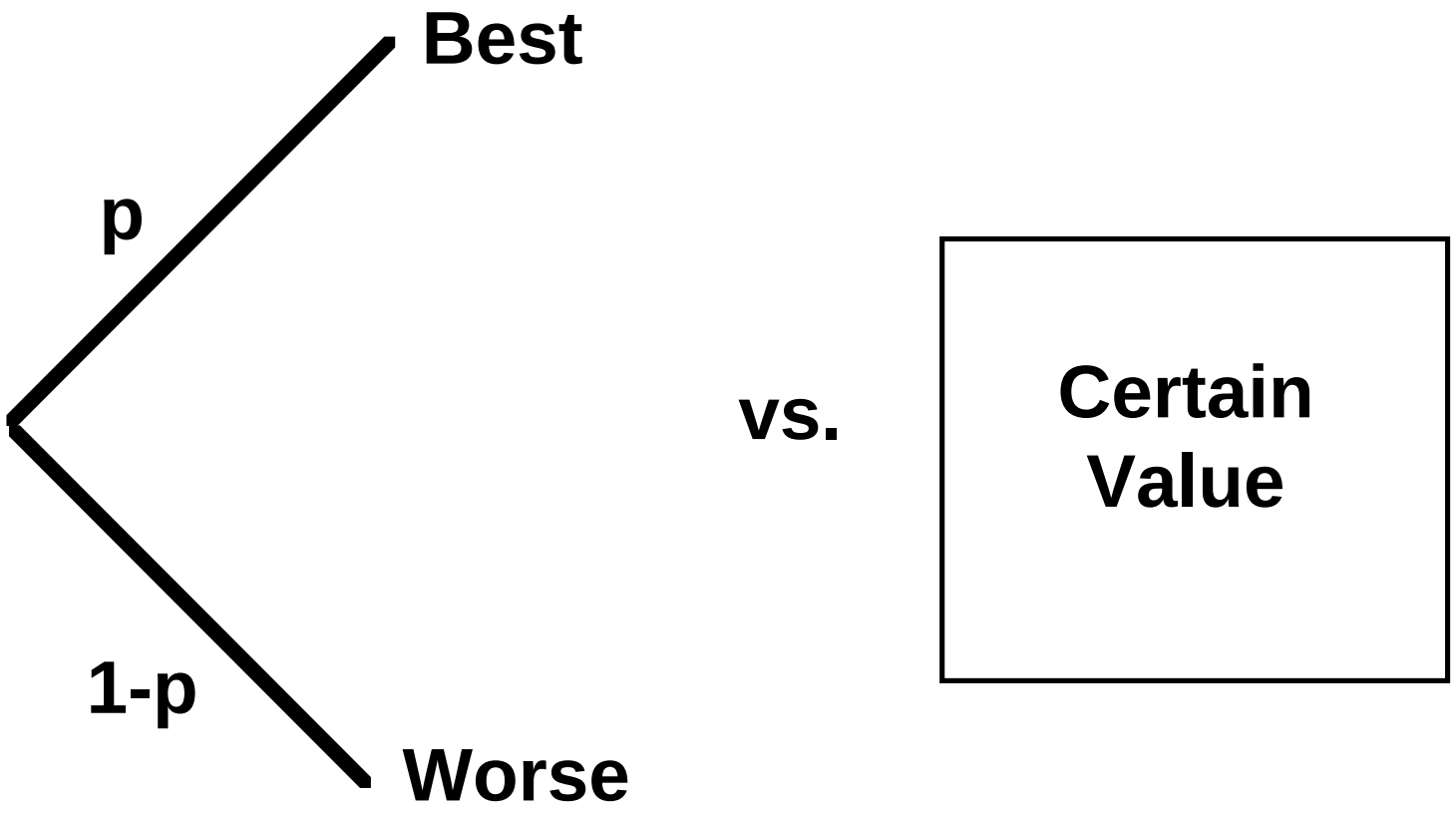
Cyanate Ester - New Material

- So New, No Market Price; Only Test Samples Available
- Promoted as Next, Best Materials
- Preceding Figure Indicates That the Material Price MUST be Such That the Board Price Does Not Exceed $2,200
- Cost Models Used to Evaluate Processing and Price Characteristics Necessary to Meet This Board Price

Cost Model Analysis



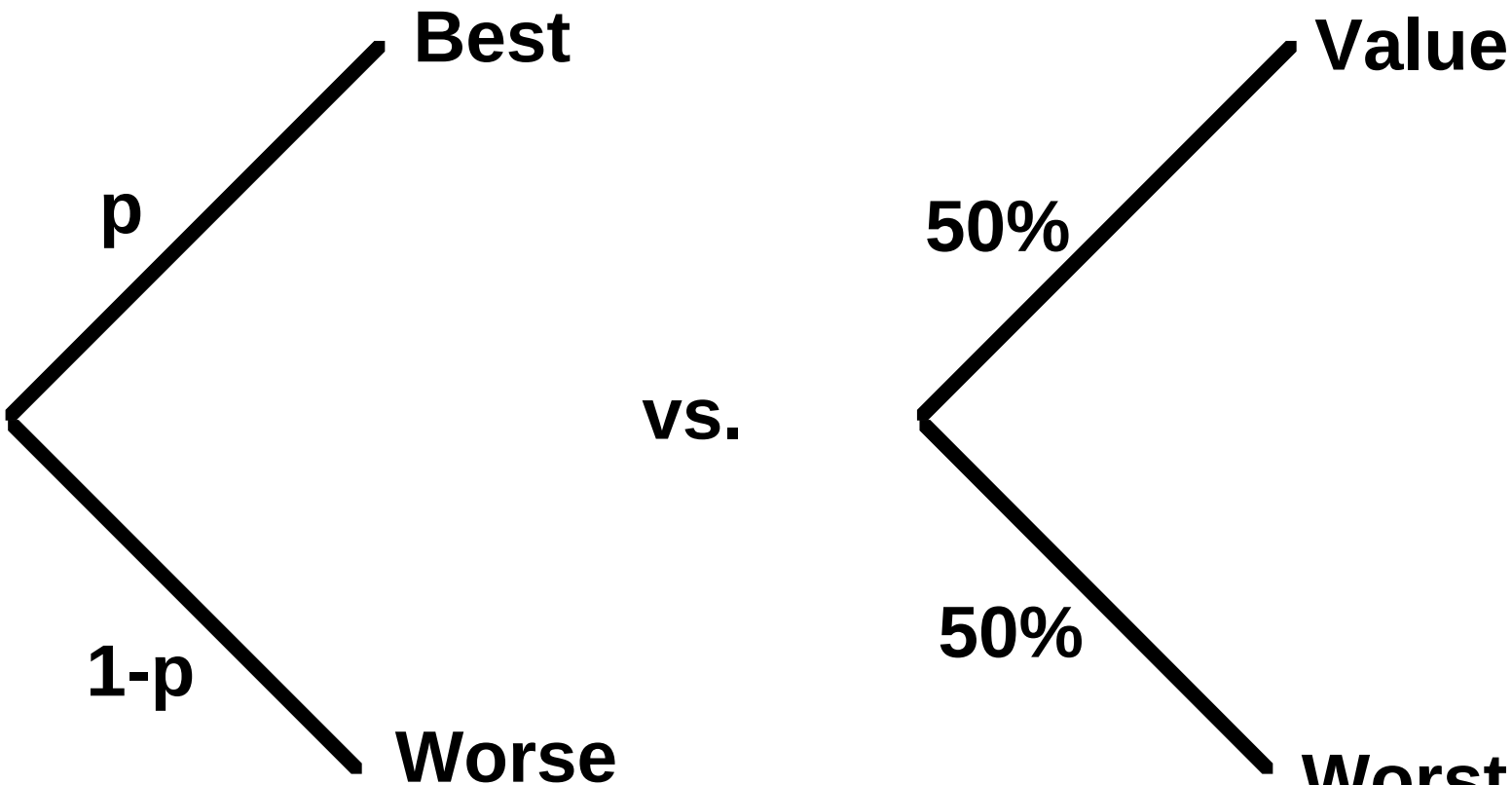
Certainty Equivalent Method



By Definition, U(Best) = 1.0; U(Worst) = 0.0

Therefore, p(1.0) = (1-p)(0.0) = U(Certain Value)

Lottery Equivalent Method



By Definition, U(Best) = 1.0; U(Worst) = 0.0
Therefore, p(1.0) + (1-p)(0.0) = 0.5(U(Value)) + 0.5(0.0)
U(value) = 2p