DEFINING MARKETS FOR NEW MATERIALS
Engineering Methodology with Case Application

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ABSTRACT

An engineering methodology to identify profitable market segments for the use of new materials is presented and illustrated by application to the automobile industry. The method has three parts: empirical, statistical and analytical. The first measures company preferences for the important attributes of a use of a material, applying single-attribute utility functions. The second identifies market segments, by determining significant differences between measured preferences with t-tests. The third estimates the premium these market segments would pay for a product made of a new material, using multiattribute utilities, and thus determines profitable market segments.

The case study of valve trains containing ceramic components defined two market segments: companies with either a broad world market or a narrow specialty. The immediate buyers of these valve trains are likely to be producers of high-value, six-cylinder automobiles, who seem prepared to pay a significant premium for this product.

INTRODUCTION

Advances in materials science and engineering have led to a proliferation of new materials with superior technical characteristics. Most of these materials are commercial failures, however. All too often, developers cannot identify profitable markets and have to abandon their efforts at considerable loss.

Science and engineering are not sufficient for the successful development of new materials. Users only adopt innovations that provide good value for money, that deliver higher performance at an acceptable cost to the user. If prospective users do not see the value in use of a new material, they will not buy it and the developers cannot hope to recapture the development costs.

Careful assessment of the value in use of new materials is thus critical to successful materials engineering. This value may be high in some uses and low in others. In short, it depends on its market. Successful development of new materials thus requires the identification of good markets, of groups of users that are prepared to pay a sufficient premium for a use of a material.

Determining the value in use of a material requires much more than economics, cost analyses or market surveys. To be precise, the value in use of something is the "utility" of its characteristics to users. This utility can be assessed accurately and reproducibly with a range of techniques that have been developed over the past decade. These methods, drawn from operations research and systems engineering, provide the basis for identifying prospective users of new materials.

This paper presents an engineering methodology to identify market segments for new materials. The first section reviews the background on utility measurement and its application to materials selection in industry. The second describes the methodology for defining good markets in detail. The third demonstrates its usefulness and practicality through a case study of the potential of structural ceramics for valve trains in automotive engines.

The methodology should be useful in many ways. Most obviously, it can help determine whether a particular material has a serious commercial future that merits substantial investment. It can focus the introduction and marketing of new materials on the customers and applications that are the best prospects. It can guide research efforts towards improving the characteristics that customers truly value.

BACKGROUND

The axiomatic basis for measuring value was set forth by von Neumann and Morgenstern.[1] Formally, a value that can be measured precisely is known as the utility of the thing or characteristic. This utility is the "value in use" of the object, and is thus always defined contextually, with specific reference to a user. The development of this concept of utility is a major achievement of applied economics, and the basis for significant advances in the understanding of how people make choices.

The utility to a user of some measurable characteristic or attribute, X_i, is a transformation of its quantity:

Utility of X_i = $U(X_i)$

In general, this transformation is non-linear: the utility of a unit of an attribute varies over its range.

Utility per unit frequently decreases as the level of a desirable attribute increases. This is because of "saturation". For example, designers value more engine power but attach less and less importance to it as the added power becomes less useful in comparison to other elements of the automobile. The phenomenon is known as "diminishing marginal utility".

Utility per unit however often increases as the level of a desirable attribute increases. This occurs whenever users have to meet an industry standard, defined either by governmental regulation or competition. From a designer's point of view for instance, the value of the strength of a bumper is close to zero until it meets regulatory standards, at which point it increases dramatically. The utility function then is logistic or "S-shaped" around this threshold.

Products usually have many attributes ($\mathbf{X}$ = X_1, X_2,...). Their value is then defined by a multiattribute utility, $U(\mathbf{X})$. Keeney[2] provided the practical, efficient way to assess multiattribute utility by decomposing it into a function of single-attribute utilities, $U(X_i)$, and scaling factors, $k(X_i)$. Specifically, this is a weighted sum modified by terms accounting for the interactions between the attributes. The formula is:

$$K\,U(X) + 1 = \prod_{i=1}^{N} (Kk(X_i)U(X_i) + 1) \qquad (1)$$

where K is a normalizing parameter that insures consistency between the definitions of $U(\mathbf{X})$ and $U(X_i)$.

The important idea to retain is that the measure of the value in use of a material can be constructed from measurements of the single-attribute utilities and the scaling factors. The measurement and application of utility have been widely applied to practical decision-making and engineering design. Keeney and Raiffa[3] and de Neufville[4] among others provide textbook presentations of the subject. Field,[5,6] did the seminal application to the problem of materials selection, and with Clark has since directed a wide range of industrial applications at the Materials Systems Laboratory at the Massachusetts Institute of Technology.[7,8,9,10,11,12]

Remarkable advances in the techniques of measuring utility accurately have occurred over the last decade. McCord demonstrated the advantage of using "lottery equivalents" to the avoid systematic errors associated with the textbook "certainty equivalents".[13,14] Delquie and de Neufville developed an efficient, computer-based "expert system" (ASSESS) to apply this approach,[15] and have used it effectively in practice.[16,17]

This theory, industrial experience and methodology provide the basis for determining profitable markets for new materials. The essential idea is to determine market "segments", that is, clusters of like-minded customers who are likely to use the new products.[18]

METHODOLOGY

The procedure for determining profitable market segments has three elements. It consists of the:

- Survey of the range of possible customers, to see how they value relevant attributes of a new product;
- Organization of these customers into clusters of users with similar values; and
- Determination of the importance of these market segments for the manufacturer of the new product.

These steps translate into specific engineering methods. As described in detail below, they are the:

- Empirical assessment of the utility of prospective users for the attributes of product using a new material;
- Statistical analysis based upon the estimated means and standard deviations of the measured utilities; and
- Determination of the multiattribute utility of the clusters of like-minded prospective users, and the estimation of the money they would be willing to pay for the new product.

Assessment of Utilities: The way to determine a person's values for different attributes is to interview them directly. To obtain precise, reproducible data, the researcher must carefully design a questionnaire, paying close attention to the sequence and type of questions.

As part of the questionnaire design, the analyst must identify the most important attributes of the product (X_i), through discussions with the prospective users. The analyst must then also specify a consistent range of each attribute that will be examined. This range establishes reference points for the utility measurements. It can be arbitrary so long as it encompasses all the values likely to be considered in practice. The range of these attributes is normally specified as $[X_{i*}, X_i^*]$, where X_{i*} and X_i^* are the worst and best values of attribute X_i.

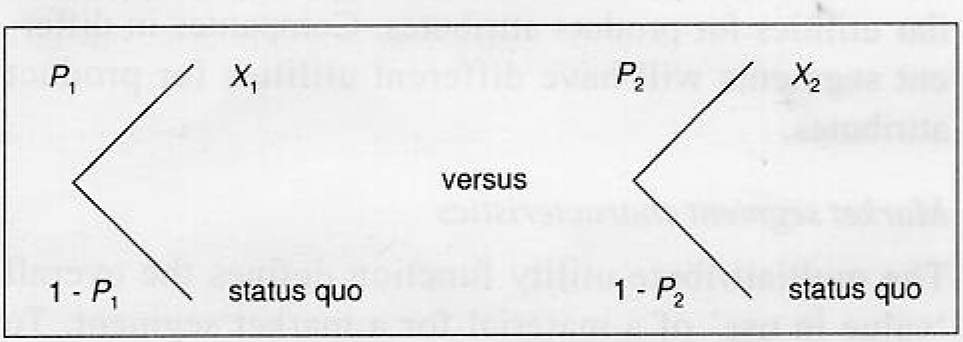

Figure 1 The probability equivalent lottery

The analyst must also identify the persons among the user groups who would be making the decisions about the use of new materials. Typically these are the lead designers for the parts being manufactured, and these are the persons whose utilities need to be assessed.

For efficiency in practical applications, the utility questionnaire is incorporated in the ASSESS program and presented to the person being interviewed on a computer screen. The computerized interview has three main advantages: it provides a controlled environment, permits easy graphical explanations of the process, and leads to rapid analysis of the data.

The interview process develops two kinds of information for each respondent, m. The first concern the person's relative value for the different attributes, the scaling factors, $k_m(X_i)$. These are used to construct the multiattribute utility used in the final analysis. The immediately important data are the "probability equivalents", $p_m(X_{i,j})$, which represent the person's relative utility of different levels, j, of the attribute, X_i. These are used to define each person's single-attribute utility function, $U_m(X_i)$.

Single-attribute utility functions can be approximated by fitting an appropriate function to the points where utility is measured. A most common form of the utility function is the exponential approximation.[17,18,19] This has the general form:

$U_m(X_i) = a_m(X_i) \{| X_i - b(X_i) | \exp [c_m(X_i)] \}$ (2)

In practice, a person's single-attribute utility is defined by the exponent $c_m(X_i)$. The convention is that the utilities at the end of the range of interest of the characteristic are defined conveniently, much as the range of a temperature scale is set at 0 and 100 degrees:

$U(X_{i*}) = 0$ and $U(X_i^*) = 1.0$ (3)

The other two parameters then depend strictly on this range:

$a_m(X_i) = | X_i^* - X_{i*}| \exp [- c_m(X_i)]$ (4)

$b_m(X_i) = X_{i*}$

The exponent $c_m(X_i)$ specifies the shape and the nature of the utility function. When $c < 1.0$, the upwards slope of the utility function decreases steadily, reflecting diminishing marginal utility for improvements in an attribute -- this is the most common pattern. When $c > 1.0$, the function reflects increasing marginal utility -- this is the usual pattern as an attribute increases toward a threshold value that marks a competitive or performance breakthrough. If $c = 1.0$, the value of the attribute is directly proportional to its level -- this is almost never observed in practice, even though several valuation schemes assume this to be the case (see the discussion in Field[7]).

For any particular measurement of a person's utility at a level, j, of the attribute, X_i, the exponent is defined by:

$c_m(X_{i,j}) = \mathrm{Ln}[U_m(X_{i,j})] / \mathrm{Ln}[| X_{i,j} - X_{i*}| / | X_i^* - X_{i*}|]$ (5)

This result comes directly from the exponential formula, using the conventional values for $a_m(X_i)$ and $b_m(X_i)$.

Reliable estimates of a person's utility require several estimates. The procedure is to assess a person's utility at several levels, each leading to a different estimate of the exponent, and to average the results. Any person's single-attribute utility function is thus defined by the average exponent, $\overline{c_m(x_i)}$.

The accuracy of the measurement process is defined statistically by the standard deviation, $s_n(X_i)$, of all the estimates of the exponent, for all levels of the characteristic and all persons. The error in measuring the exponent is taken to be a percentage deviation from the average value for each person. The actual measurements for each person are thus normalized with respect to the average value $\overline{c_m(x_i)}$, pooled with the measurements for other persons, and used to derive the standard deviation of the measurement process.

Definition of Market Segments: A market segment is a cluster of customers who have comparable values. Operationally, defining a market segment consists of identifying customers whose utilities are both comparable to each other and different from those of other groups.

The procedure for defining market segments consists of applying statistical tests to the measurements of utility for the customers. Specifically, it applies t-tests to the null hypotheses that the $\overline{c_m(x_i)}$ values for sets of customers are the same. For efficiency, the statistical tests should focus initially on the natural groups within an industry.

A first analysis should compare the utility functions of decision makers in the same company. Are their values statistically equivalent within a sufficient degree of confidence, such as 95%? If yes, then it is reasonable that the average of their exponents defines a measure of the values to that company of the attribute being examined. If no, then it would seem that the several decision-makers within the company are divided, and it may not be possible to obtain a good reading on the values of that company. As a practical matter over the years, we have found that companies do develop a "corporate culture" about how they value attributes, and that it is possible to estimate their values from measurements taken on key individuals.

The next step should examine the market groups traditionally associated with each company. Are the values of these companies statistically equivalent within a sufficient degree of confidence, such as 95%? The analysis is similar to that performed for individual respondents within a company. These market groups may well represent market segments that have similar values for the characteristics of a material. However, to the extent that these groups represent historical or geographical categories (European manufacturers for example) rather than real similarities in the way they use materials, the traditional groups may not really represent market segments.

The last step in establishing market segments is to consider companies that seem to value material characteristics similarly. The analysis is identical to those performed before. The difference is that the possible number of combinations may be large. In practice however, the differences between companies limit the possibilities.

The final result will be two or more market segments. Each market segment is characterized by a single-attribute utility function, defined by the average of the exponents of the utility functions of each company in the market segment. Companies within each group will value attributes of a product similarly. Companies in different segments will value these attributes differently.

Market Segment Characteristics: The multiattribute utility function defines the overall value in use of a material for a market segment. To identify profitable market segments for products using new materials it is thus necessary to:

1. Define the multiattribute utility function for each market segment;
2. Calculate the premium the market segment might pay for the use of a product made of the new material; and
3. Compare this premium to the cost of supplying the product in the new material, thus determining profitable opportunities.

The multiattribute utility function for each market segment is determined by two factors:

1. The single-attribute utility functions for each attribute, as defined by the average exponents for the group; and
2. The scaling factors $k(X_i)$, calculated as the average value of those of each company in the group.

The scaling factors define the normalizing parameter K and thus the multiattribute utility according to Equation (1). See de Neufville[5] for a textbook explanation of these mechanics.

The premium that a market segment might be prepared to pay for a product using the new material can be determined by comparing the multiattribute utility of the product with the new material to that of the product using the best traditional material. Naturally, the utility of the product with the new material depends on its price. It rises for lower prices and decreases for higher price.

A market segment of customers will prefer a product using a superior new material if the price is low enough. It will continue to do so as the price of the product increases, until its utility equals the utility of the product using the traditional material. This point is the "break-even price". It is defined graphically by the intersection of the utility curve for the product using the new material, with the reference utility for the product using the traditional material at the prevailing price. Figure 2 illustrates the situation.

The premium a market segment might be prepared to pay for a product using the new material is the difference between the break-even price and the prevailing price for the traditional material.

The premium is only defined within a range. This is because measurement errors necessarily only define the utility functions within confidence limits. The confidence limits on the utility function define a "break-even range", as Figure 2 indicates.

The potential profitability of a market segment is determined directly from this information. It is the difference between the premium and the cost of producing a product with the new material. This profitability depends, of course, on both the application and the market segment.

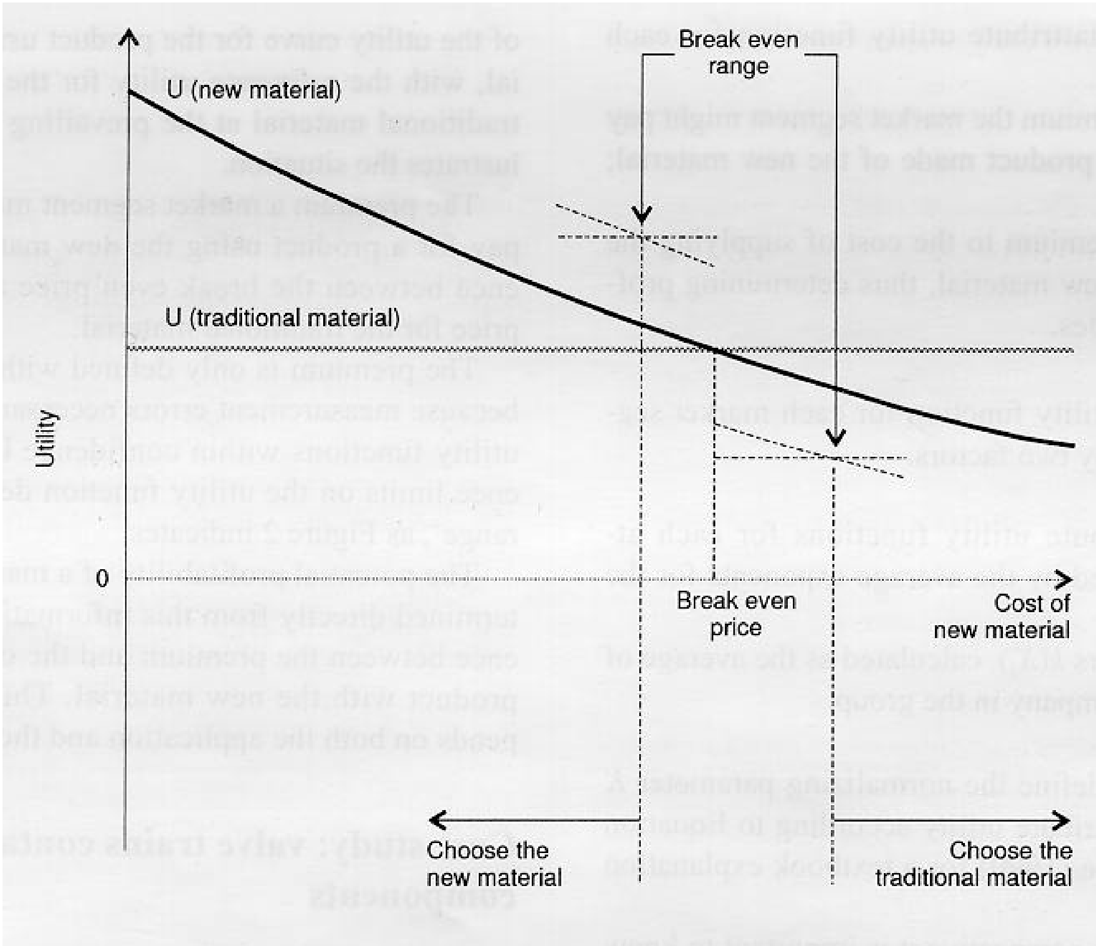

Figure 2 Multiattribute utility functions define the premium that market segments may pay for the use of a new material

CASE STUDY: VALVE TRAINS CONTAINING CERAMIC COMPONENTS

Ceramic components in automotive valve trains can improve performance in many ways. Being lighter, they improve the dynamic behavior of the valve train, increasing its durability and reducing noise; and allow lower forces on the valve springs, reducing frictional losses and improving fuel economy. Their lower mass also permits improvements in the timing and lift characteristics of the valves and thus increases engine power.[19] Figure 3 summarizes these advantages.

These improvements in engine performance can be significant. Under highway road conditions (engine speed around 1500 rpm), bench test comparisons of the performance of the valve train with different materials[20] indicate that ceramic components could lead to:

1. 5% increase in maximum engine power;
2. 16% reduction in noise; and
3. 11% reduction in engine friction.

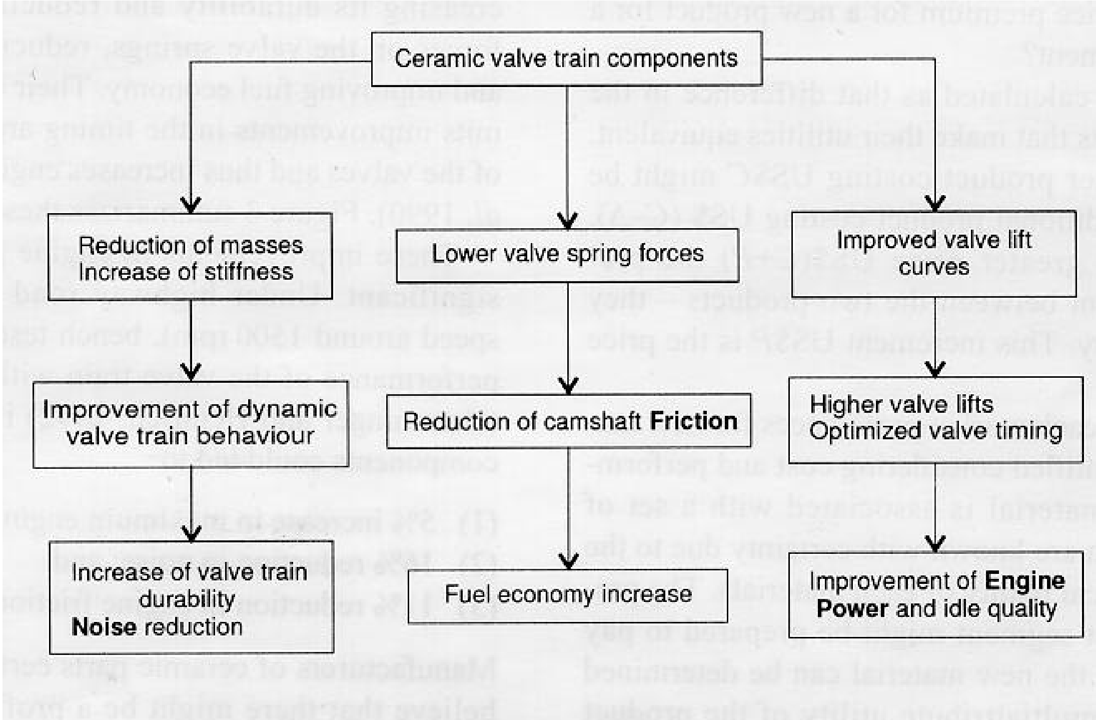

Figure 3 Ways in which ceramic valve trains improve engine performance

Manufacturers of ceramic parts certainly have reason to believe that there might be a profitable market in ceramic components for automotive valve trains. What might that be? Specifically, which automobile manufacturers might be most interested in using this new material in this application?

The investigation of this question demonstrates the usefulness of the methodology for identifying markets for new materials. The work was done at the MIT Materials System Laboratory, in cooperation with a wide range of industrial partners among automobile manufacturers in North America and Europe.

Assessment of Utilities: The most important attributes of ceramics in this application were determined in consultation with auto makers in the United States and in Europe. The following were selected for inclusion in the analysis:

1. Cost;
2. Engine power, expressed in horsepower per liter of engine combustion volume;
3. Friction Pressure, representing the overall friction on the valve train; and
4. Noise.

Decreases in cost, friction pressure and noise are all desirable. Greater engine power from an existing design is also an improvement. Table 1 gives the ranges considered.

Table 1: Ranges for the Material Characteristics.

Attribute	Units	Worst Value, X∗	Best Value, X*
Cost	Dollars	224	37
Engine Power	HP/l	30	115
Friction Pressure	Bars	2	0.25
Noise	dB	70	50

To obtain the values of the companies for these attributes, Mangin interviewed the designers. Extensive experience with the automotive industry indicates that they have extensive powers of decision and great influence in the selection of engine materials.

Mangin's interviews generated data for the values of 21 designers, for 8 major automobile manufacturers, for each of the 4 attributes.[21] This is perhaps the largest such database ever collected. It certainly provided ample basis for the preliminary determination of interesting market segments for the implementation of ceramic components in valve trains.

Definition of Market Segments: The comparison of the utility functions of decision makers in the same companies indicated clearly that the different designers each represented their company's "corporate culture" regarding the choice of materials. The t-test applied to the data demonstrated over 95% confidence in this conclusion.

Two market segments were identified by comparing the companies:

1. A Narrow Market, represented by companies which focus on either a specific geographic market (Fiat, Peugeot, Renault) or on a specific product line market (Mercedes); and
2. A Broad Market, represented by auto makers targeting a world market with a diverse product line (Chrysler, Ford, General Motors, and Volkswagen).

This partition emerged from the raw data. As shown in Figure 4, the average values of the exponents defining the utility for costs of the companies split rather obviously into a high group and a low group. The companies associated with each group then constituted the market segments described.

The market segments were validated statistically. Since the values of the utility exponents for cost for one group were lower than those in the other, a one-sided t-test was appropriate. This demonstrated that there was only a 1% chance that the two groups are statistically identical.

The "Broad Market" segment is "risk averse" with respect to the cost of the valve train. It has diminishing marginal utility as indicated by the mean exponent of the single-attribute utility:
Broad Market $c(\text{Cost}) = 0.809 < 1$.
This means that, in this case, these companies prefer to have a known cost for sure rather than take a chance that they might save costs at the possible price of cost increases. They are thus relatively unwilling to try parts using new materials.

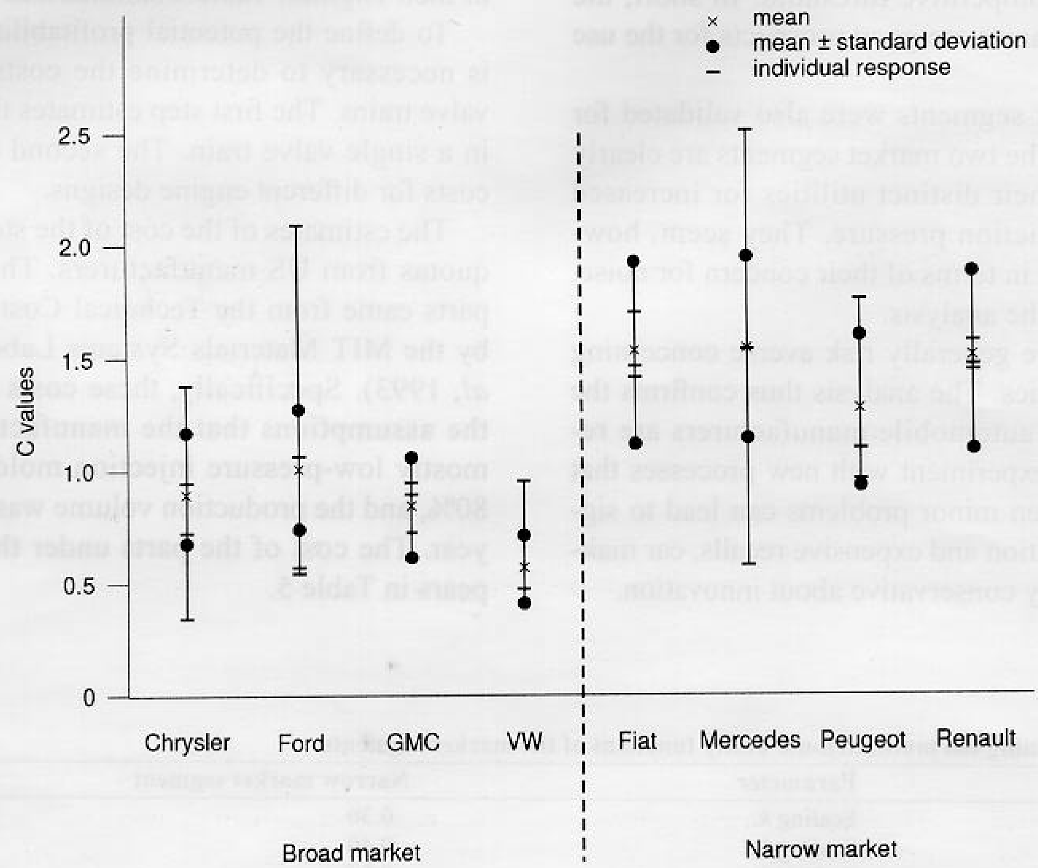

Figure 4 Pattern of company valuations of cost

The "Narrow Market" segment on the other hand is "risk positive". Its increasing marginal utility for reducing costs is indicated by the mean exponent of the single-attribute utility:
Narrow Market $c(\text{Cost}) = 1.347 > 1$.
This means that these companies are prepared to absorb some increases in cost for the possibility that they could achieve a substantial breakthrough. To the extent that they cater to the smaller market of more expensive automobiles, they can reasonably expect to pass extra costs on to their customers. Their willingness to take financial risks is a classic example of companies seeking to cross a competitive threshold. In short, the "Narrow Market" companies are good prospects for the use of new materials.

These two market segments were also validated for the other attributes. The two market segments are clearly distinguishable by their distinct utilities for increased engine power and friction pressure. They seem however to be equivalent in terms of their concern for noise. Table 2 summarizes the analysis.

Table 2: Exponents defining the Single-Attribute Utility Functions of the Market Segments

Attribute	Narrow Market Segment	Broad Market Segment
Cost	1.35	0.81
Engine Power	0.51	0.72
Friction Pressure	0.85	1.10
Noise	0.81	0.81

The companies are generally risk averse concerning technical characteristics. The analysis thus confirms the expectation that the automobile manufacturers are relatively reluctant to experiment with new processes that risk failure. Since even minor problems can lead to significant loss of reputation and expensive recalls, car makers are understandably conservative about innovation.

The "Narrow Market" segment is clearly more conservative on the technical characteristics than the "Broad Market" companies. This is possibly because the "Narrow Market" segment aims toward more expensive vehicles, whose performance is important.

Interestingly, the "Broad Market" segment is not conservative about improvements in friction pressure. It even seems inclined to experiment. This is possibly because this segment consists of manufacturers either in the U.S. or for whom the U.S. market is important. Their more aggressive behavior on this issue is thus perhaps driven by the strong American regulations on fuel economy.

Market Segment Characteristics: The multiattribute utility functions for the two market segments are defined by the parameters shown in Table 3.

Table 3: Parameters defining the Multiattribute Utility Functions of the Market Segments

Attribute	Parameter	Narrow Market Segment	Broad Market Segment
Cost	Scaling k	0.30	0.52
Engine Power	" "	0.40	0.33
Friction Pressure	" "	0.30	0.40
Noise	" "	0.28	0.28
All	Normalizing K	- 0.51	- 0.74

The premiums the automobile manufacturers are willing to pay to achieve the performance made possible by ceramic components depend on two factors:

1. The market segment, since this defines the utility the companies place on improved performance; and
2. The engine design, which defines the cost and the utility of using the traditional material (steel in this case).

These premiums can be substantial. They are particularly important for the "Narrow Market" companies, the ones prepared to take some financial risks in the design of their engines. Table 4 summarizes the results.

Table 4: Premium Designers Are Willing To Pay To Achieve the Performance made possible by Ceramic Components

Engine Design	Market Segment	Premium $	Uncertainty +/- $
Six Cylinder	Broad	34	11
	Narrow	95	8
Four Cylinder	Broad	14	1
	Narrow	115	10

To define the potential profitability of the markets it is necessary to determine the costs of the producing the valve trains. The first step estimates the costs of the parts in a single valve train. The second calculates the total costs for different engine designs.

The estimates of the cost of the steel parts came from quotes from U.S. manufacturers. Those of the ceramic parts came from the Technical Cost Models developed by the MIT Materials Systems Laboratory.[22] Specifically, these costs were estimated on the assumptions that the manufacturing process was mostly low-pressure injection molding, the yield was 80%, and the production volume was 3 million parts per year. The cost of the parts under these conditions appears in Table 5.

Table 5: Cost of Metal and Ceramic Components

Component	Metal Cost, $	Ceramic Cost, $
Exhaust Valve	1.50	3.80
Intake Valve	0.80	4.30
Roller Follower	0.50	2.90

The cost of making a engine with ceramic components in the valve train depends both on the number of parts used and on the number of cylinders and valves in the engine. The analysis considered two possibilities for replacing parts. One case only used ceramic exhaust and intake valves, the other also used ceramic roller followers. The analysis considered four possible engine designs: 4 and 6 cylinder engines, each with 2 or 4 valves per cylinder. Table 6 summarizes the extra costs of using ceramic rather than steel components for all these cases.

Table 6: Extra Costs of Using Ceramic rather than Steel Components in Various Engine Designs

Engine Design	Valves	Replacing Valves Only, $	Replacing Valves and Follower, $
Six Cylinder	24	83	141
	12	35	64
Four Cylinder	16	31	74
	8	23	42

The potential profitability of the different market segments is established by comparing the premium designers are prepared to pay and the cost of using the new material in different designs. Tables 7 and 8 summarize the possibilities. This tabulation makes it clear that "Narrow Market" segment of companies are most likely to be the immediate users of ceramic parts in automobile valve trains.

Table 7: Potential Profitability In Narrow Market Segment of Using Ceramic rather than Steel Components in Various Engine Designs

Engine Design	Valves	Replacing Valves Only, $	Replacing Valves and Follower, $
Six Cylinder	24	4	(54)
	12	52	23
Four Cylinder	16	84	41
	8	92	73

Table 8: Potential Loss In Broad Market Segment of Using Ceramic rather than Steel Components in Various Engine Designs

Engine Design	Valves	Replacing Valves Only, $	Replacing Valves and Follower, $
Six Cylinder	24	(49)	(107)
	12	(1)	(30)
Four Cylinder	16	(17)	(60)
	8	(9)	(28)

CONCLUSION

The methodology works well. This is largely because it is based on proven, straightforward techniques. It is not limited, either to the type of materials or to the product. Its conceptual simplicity and ease of use should make it useful in many situations.

ACKNOWLEDGMENTS

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REFERENCES

1 John von Neumann and Oscar Morgenstern, *Theory of Games and Economic Behavior*, 2nd. ed., Princeton University Press, Princeton, NJ, 1947.

2 Ralph Keeney, 'Utility Independence and Preferences for Multiattributed Consequences,' *Operations Research*, Vol.19, 1971, pp.875-893.

3 Ralph L. Keeney and Howard Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs,* John Wiley & Sons, New York, NY, 1976.

4 Richard de Neufville, *Applied Systems Analysis: Engineering Planning and Technology Management*, McGraw-Hill Publishing Co., New York, NY, 1990.

5 Frank R. Field, III, *Strategy Analysis of Materials Using Multi-Attribute Utility Analysis,* Ph.D. Thesis, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1985.

6 Frank R. Field, III and Richard de Neufville, 'Materials Selection - Maximizing Overall Utility,' *Metals and Materials,* Vol. 4, No.6, June 1988, pp. 378-82.

7 Deborah Thurston, *Multiattribute Utility Analysis of Materials Selection Decisions*, Ph.D. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1987.

8 Deborah Thurston, 'A Materials Selection Tool for Automotive Structural and Body Skin Systems,' *SAE Materials Transactions*, 886303, 1988.

9 Narayan Nallicheri, *A Technical and Economic Analysis of Alternative Net Shape Processes in Metals Fabrication,* Ph.D. Thesis, Materials Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 1990.

10 Narayan Nallicheri, Joel Clark and Frank Field, III, 'Material Alternatives for the Automotive Crankshaft: A Competitive Assessment Based on Manufacturing Economics,' *Society of Automotive Engineers,* Paper 910139, International Congress and Exposition, Detroit, MI, 1991.

11 Richard Roth, *Materials Substitution in Aircraft Gas Turbine Engine Applications,* Ph.D. Thesis, Materials Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 1992.

12 Richard Roth, Frank Field III and Joel Clark, 'Materials Selection and Multi-Attribute Utility Analysis,' *Journal of Computer-Aided Materials Design*, Vol.1, 1994, pp. 325-342.

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[13] Mark McCord, *Empirical Demonstration of Utility Dependence on the Fundamental Assessment Parameters*, Ph.D. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1983.

[14] Mark McCord and Richard de Neufville, '"Lottery Equivalents": Reduction of the Certainty Effect Problem in Utility Assessment,' *Management Science*, Vol. 32, No. 1, 1986, pp. 56-60.

[15] Philipe Delquié, *Contingent Weighting of the Response Dimension in Preference Matching*, Ph.D. Thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA, July 1989.

[16] Richard de Neufville and Daniel King, 'Risk and Need-for-Work Premiums in Contractor Bidding,' *ASCE Journal of Construction Engineering and Management*, Vol.117, No.4, Dec.1991, pp.659-673.

[17] Richard de Neufville and J.T.Smith, 'Improving Contractors' Bids by Exploiting the "Preference Reversal" Phenomenon,' *ASCE Journal of Construction Engineering and Management*, Vol.120, No.4, Dec.1994, pp.706-719.

[18] Glen Urban and John Hauser, *Design and Marketing of New Products*, Prentice-Hall, Englewood Cliffs, NJ, 1980, pp. 250-251 and 272-278.

[19] G. Rogers, R. Southam, J. Reinicke-Murmann and P. Kreuter, 'Analysis of Potential Improvements in Engine Behavior Due to Ceramic Valve Train Components,' *SAE International Congress and Exposition*, SAE Paper No. 900452, February 26-March 2, 1990.

[20] Rainer Hamminger and Juergen Heinrich, 'Development of Advanced Silicon Nitride Valves for Combustion Engines and Some Practical Experience on the Road,' *Materials Science Society*, MRS Paper K7.4, MRS Fall Annual Meeting, Boston, MA, 1992.

[21] Christophe Mangin, *Advanced Engineering Materials for Automotive Engine Components: Cost and Performance Estimations*, Ph.D. Thesis, Materials Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 1993.

[22] Christophe Mangin, J. Neely III, and Joel Clark, 'The Potential for Advanced Ceramics in Automotive Engine Applications,' *Journal of Metals of the American Society for Metals*; Metals Park, OH, June, 1993.