Multi-attribute utility analysis (MAUA) has emerged as a powerful tool for materials selection and evaluation. An operations research technique, MAUA has been used in a wide range of engineering areas, of which materials science and engineering is one of the more recent. Utility analysis affords a rational method of materials selection which avoids many of the fundamental logical difficulties of many widely used alternative approaches.

However, MAUA has traditionally been used in materials selection problems only in which there is certainty regarding the attribute levels of the alternatives. For many new technologies this is not the case. Another operations research technique, subjective probability assessment (SPA), can be used to address this issues. SPA makes it possible to develop a distribution of attribute levels when there is uncertainty in these values. These probability distributions can be used in conjunction with MAUA to provide a consistent framework for making materials selection decisions. Furthermore, the use of these techniques extends beyond the problem of materials selection into the more speculative areas of materials competitiveness and market demand, even in cases involving new, as of yet unproven technologies.

**Materials Selection**

The selection of a material system for an engineering application requires the designer to find the best match between the technical and economic requirements of the application and the performance and manufacturing characteristics of the available material alternatives. The identification of this best match is frequently a difficult problem, relying upon the designer's accumulated experience, expertise, and judgment.

Materials selection has emerged as a major problem for engineers. The available set of materials, rapidly growing both in type and number, has vastly expanded the number of possibilities meriting serious consideration for many engineering applications. At one time, an engineer could rely upon engineering handbooks, journals, and his experience to select the appropriate material for an application. Today, however, engineers are forced to look for systematic techniques for managing and analyzing engineering data on the growing array of materials.

At the same time, the suppliers of materials face an equally perplexing problem. While advances in materials science continue to expand the horizons of material performance, the material developer finds it increasingly difficult to establish what constitutes a desirable material. By its nature, the designer's process of material selection happens outside the ken of the suppliers of the material alternatives. Because the suppliers are frequently isolated from this process, they receive little insight into the rationale for the success or failure of their offerings. The lack of this information not only limits their ability to identify and rectify the limitations of their current offerings, but it also makes it very difficult to ascertain what success new offerings will have.

These difficulties are a consequence not only of the ever-increasing number of material alternatives available, but also of the very nature of the materials selection problem. While several analytical tools have been developed to cope with the former problem (notably screening and indexing techniques [1,2,3,4,5,6,7,8]), none of them successfully treats the latter [9,10].
When evaluating competing material alternatives, the analyst is called upon to identify the 'best' alternative for the application under consideration. The identification of this 'best' alternative is quickly complicated by two elements of the materials selection decision. First, the indices of performance of a particular material alternative are incommensurable on any objective basis (e.g., yield strength and tensile modulus). While the application of design constraints and engineering relations can occasionally yield analytical relationships which can be exploited for design purposes (for example, thickness, modulus, and curvature relations for calculating plate stiffnesses), there are no global relationships which are able to transform complex measures of performance, like cost and manufacturability, into analytical design relations.

Second, there are no such global analytical relationships because, by their very nature, they cannot incorporate the essence of the design process, which is the use of engineering judgment to develop strategies for solving multi-objective problems. For example, all automobile body panel designers might agree on two facts, all other factors equal: (1) lower cost body panels are always preferred, and (2) lower weight body panels are always preferred. If so, it is easy to predict that $50, 25 pound panels will always be preferred over $100, 40 lb. panels (all other things equal).

On the other hand, it is a very different matter when the alternatives are a $100, 25 lb. panel and a $50, 40 lb. panel. If asked to identify the better of the two alternatives, the usual answer is "it depends." The reason for this response is that the simple decision rules are deficient when there is no single alternative having attributes no worse than the best offered by any other alternative; there is no 'dominant' alternative. Rather, the choice must be made from members of the 'non-dominated' set of alternatives. And the selection of the 'best' from this set of alternatives cannot be made on the basis of objective rules; subjective judgments by the designer will determine the preferred alternative.

Returning to the above example, a designer developing a low performance, high volume automobile on a tight production budget would probably select the $50, 40 lb. panel. On the other hand, the same designer working on a high performance, low volume application might lean toward the $100, 25 lb. panel. There is no inconsistency here; rather, the designer's preferences (which might themselves be driven by product strategies, corporate policies, government regulations, etc.) enable him to trade-off these incommensurable characteristics in order to select the alternative which best meets his design goals.

Further complicating the situation is the issue of uncertainty. Often the value of one or more of the incommensurable characteristics is not known with certainty. This is often true with decisions involving new technologies.

A modification of the previous example will illustrate this point. Consider the use of a new, unproven material for automotive body panels. In this case there is uncertainty surrounding both the cost and the weight of the panel. While a manufacturing cost may be estimated, until panels of the alternative materials go into production, it is impossible to know exactly the cost. The same may also be true of weight. Prior to production, part weight can only be estimated. The manufacture and use of the new material may necessitate design changes which result in changes in part weight.

The lack of certainty add another dimension to the selection process. The decision maker now must not only make trade-offs between incommensurable characteristics, but also must consider
perceptions of the likelihood of the new alternative achieving predicted attribute levels. In turn, the selection now depends not only on the relative preferences of the attributes, but on the personal perceptions and biases of the decision maker with regard to the new alternatives.

**Multi-Attribute Utility Analysis**

Efforts to understand how this choice takes place, and to help people make the most effective use of the information that they have to make these choices, have led to the development of a branch of operations research known as decision analysis. Within this field, researchers into multi-objective problem solving have formulated the theory of utility analysis, which has been applied to great effect in many engineering fields.

A utility function is a mapping of a multi-dimensional attribute space into a single dimensioned preference space. A simple attribute space (cost and weight) was considered above. The critical elements of this attribute space are that its dimensions correspond to the performance attributes that underlie the decision being studied, and that the limits of this space are well defined at the outset of the analysis. Based upon repeated evaluations of carefully constructed decision problems, an analyst can define a mathematical mapping of this performance space into a single dimension of preference, which establishes an ordering to all points in the attribute space. The defining characteristics of any utility function are:

Given two alternatives, \( A \) and \( B \), and a utility function \( U(x) \)

- \( U(A) > U(B) \) if \( A \) is preferred to \( B \); and
- \( U(A) = U(B) \) if \( A \) and \( B \) are equally preferred

While there are a wide range of potential transformations which can meet these criteria, decision analysis focuses upon a subset of utility functions, classified as 'von Neumann-Morgenstern utility functions.' Such utility functions are characterized by the fact that they are consistent under probabilistic expectation, i.e. if an individual is indifferent between a given alternative \( A \), and a situation in which there is a probability \( p \) that alternative \( B \) will obtain and a probability \( (1-p) \) that alternative \( C \) will obtain, then \( U(A) = p \ U(B) + (1-p) \ U(C) \). Graphically this is represented as a lottery of the following form:

\[
\begin{array}{c}
A \\
\sim \\
B \\
\downarrow 1-p \\
C
\end{array}
\]

This characteristic of von Neumann-Morgenstern utility yields a powerful ability; utility functions of this form can be successively approximated through repeated inquiries under which individuals are asked to make choices under uncertainty. For example, by offering a subject a choice between \$10 and a 50:50 chance of winning \$X (versus a \$0 outcome) and by varying \( X \), it should be possible to establish the relative utilities of \$10, \$0, and the value of \( X \) which makes the subject just indifferent between the alternatives. Persistent questioning could yield a fairly detailed mapping of dollars onto utility space, limited only by the subject's patience and the
questioner's persistence. Such a utility function could be used to predict the subject's choice in any situation falling within the domain of the measured space.

It is important to recognize that the scale of measurement is defined by the analyst at the outset of the analysis; extrapolation of utility functions outside the boundaries of measurement cannot be reliably accomplished. However, within the measurement boundaries, fairly detailed definition of the utility function can be accomplished with relatively few inquiries.

While such single attribute utility functions do have their uses, it is through the extension of this concept to multiple dimensions that it becomes literally possible to compare apples with oranges, and then suggest which is better in the eye of a particular beholder. The extension of the von Neumann-Morgenstern framework to multi-attribute utility functions resolves the question of interdimensional incommensurability through the development of utility functions which treat several attributes simultaneously, without a geometric increase in measurement complexity.

This technique has been widely used within the engineering community to considerable success. Within the past decade, the use of this technique has been extended to the analysis and evaluation of problems of materials selection. The problem by its very nature parallels the problems for which multi-attribute utility analysis was developed to address, and it has been successfully applied to the study of this class of problems.

A feature of utility functions which makes them particularly valuable in these analyses is the fact that utility is not a simple ordinal measure; rather, utility is a cardinal measure over the range of measurement. Thus, an inverse utility function is meaningful, and it can be used to identify the degree to which individual attributes of a decision alternative should change to achieve a desired level of utility. This fact suggests that it is possible, through the use of this technique, to go beyond simple ordering of a complex set of alternatives, and to actually quantify the degree to which one alternative surpasses the others in terms of performance attributes, like cost and weight.

Traditionally, the use of MAUA in materials selection decisions has been limited to cases in which there is exact knowledge of the attribute levels. This is a reasonable expectation for existing technologies, but in the case of new alternatives, it is often difficult to state with accuracy the levels of the relevant characteristics. Often the materials is only being produced on an experimental scale. Testing of materials under these conditions can yield results which are vastly different from those seen in the same material processed on a large production scale. Furthermore, testing is usually conducted on small laboratory specimens, which may not necessarily represent the behavior of the material in a larger part with a complex geometry. Additionally, laboratory test conditions may not accurately reflect the operating conditions the component will have to endure. Also, performance levels for new materials are usually available only from the potential material supplier and may thus be reported in a biased manner so as to cast the results in the best possible light. This bias is further compounded by biases against new materials on the part of the end users. Finally, in many cases, new materials are still in the experimental stage and accordingly only projected values for their levels of performance characteristics are available. Even if these projections are reasonable, there is still some probability that they will not be achieved.
For all of these reasons there is some uncertainty concerning the levels of attributes for new materials and technologies. However, this does not mean that MAUA is useless. On the contrary, MAUA is designed to deal with exactly this situation. In past materials selection problems, single attribute utility values have been calculated using well defined levels of each characteristic. In the scenario previously described, this is no longer possible. Use of values reported by materials suppliers will result in rankings of the alternatives which do not truly represent the decision makers preferences. Instead, values which represent the expectations of the performance levels must be employed. This requires examination of the degree to which the decision maker believes the values reported by the materials supplier.

Many factors can affect this situation. Company reputation may play a large role. If the decision maker has had favorable past experiences with the supplier, he may judge their results more favorably than otherwise. Past experience with the type of material may also be a major factor. If the decision maker has seen others fail in their attempts to use this material, he may be less inclined to believe the "hype" about the material. Other factors might include the decision maker's experience with other new materials and stage of development of this material. Past experience with other new materials may have led the decision maker to conclude that reported levels of attributes are systematically higher than indicated by independent testing of parts fabricated from the material. Furthermore, decision makers may treat materials from which parts have been prototyped or otherwise proven differently from those in earlier stages of development.

In the case of uncertain attribute levels, the decision can now be seen as the trade-off between two choices, each of which has a set of possible outcomes. Graphically, this can be represented as the following lottery.

The outcomes can be measured by the decision makers' expectation of the levels of the attributes for each material alternative. This can be quantified in terms of a probability distribution describing the likelihood of achieving the entire spectrum of attribute levels for each material. Integrating the product of the utility at a given point and its probability over the entire range of values of the attribute yields a corrected single attribute utility value.

\[
U(i) = \int U(x)p(x)dx
\]

Where:
- \(U(i)\) = the utility of attribute \(i\)
- \(U(x)\) = the utility of level \(x\) of attribute \(i\)
- \(p(x)\) = the probability density function

This can be used as before in calculating a multi-attribute utility value.

**Subjective Probability Assessment**

The probability density functions used to describe uncertain attribute levels can be obtained using a technique called subjective probability assessment. SPA involves measurement of ones perception of the likelihood of the occurrence of an event. There are a number of methods available to assess these values. These methods basically fall into three classifications; probability methods, value methods and probability-value methods. Probability methods involve the evaluation of the probability of the occurrence of a specific event. Value methods require the
subject to identify limits of the attributes which correspond to given probabilities. Finally, probability-value methods involve a combination of the two techniques. [11] Some of the most common techniques employed are the variable interval method and the fixed interval method. The variable interval method is a value technique which asks the subject to identify the limits of an interval of the level of an attribute which he feels will have a specific probability of containing the actual value. The fixed interval method requires the subject to assign a probability to the occurrence of the actual value lying in a specified interval. [12]

**Application of Utility Analysis**

Materials selection using utility analysis proceeds as do many of the standard techniques for materials selection, except that the criterion of choice is different. Instead of maximizing a weighted index, overall utility is maximized.

The first step is to identify the performance characteristics which are important for a particular application. There are, of course, a wide range of performance characteristics which go into the design of any engineering component. They may be gleaned from the relevant engineering literature and texts, professional societies and standards, and current industrial practice. The number of criteria can be considerably more than the limiting number of six cited above. However, rarely is it necessary to treat all of these criteria in a multi-attribute utility analysis. In most cases, the majority of these criteria are 'binary' and do not require the extensive treatment that utility analysis entails. 'Binary characteristics' are those for which there are clearly defined limits of performance; whose performance below a particular level is completely unacceptable and above which is not particularly valued by the decision maker. There are usually many such characteristics in any engineering design/materials selection problem. While in isolated cases engineering design may take into account and balance the multitude of performance criteria under consideration, most engineering designs set simple performance limits for most
characteristics and concentrate on a subset of these for the bulk of their engineering decision making.

The second step is to construct the questionnaire for measuring utility. This is a standard procedure [13]. Briefly, these questionnaires revolve around asking the subject to make pairwise choices between two alternatives offering both different levels of engineering performance and different levels of uncertainty. Two classical scenarios involve a materials acceptance scenario (i.e., choose between the available shipment of materials, which offers an uncertain level of performance, or demand a shipment that precisely offers some intermediate level of performance) or a research funds allocation problem (i.e., choose between two research programs, one which may offer better ultimate material performance, although with less certainty.)

The critical feature of the questionnaire is that it must be representative of actual decisions made by the interview subject. If the scenario presented is too unrealistic, the analyst cannot be assured of the validity of his data, nor can he be assured that his interview subject will treat the effort with any degree of seriousness. As a consequence, the development of these questionnaires calls for considerable insight and ingenuity on the part of the analyst.

If there were no issue of uncertainty regarding attribute levels, this is all that would be needed in terms of data collection. The next steps would be to calculate the utility functions and to use the known attribute levels to determine a multi-attribute utility value for each alternative. However, as already discussed, often more information is needed concerning the believability of attribute levels. In this case it is important to understand the decision makers' perceptions of attribute levels. This is readily accomplished through the use of a supplemental subjective probability assessment survey.

Typically the SPA survey would present a "predicted" value for the attribute and ask the decision maker to assign a probability. One of the previously mentioned assessment methods would then be used. The decision maker will be requested to either state probabilities for additional attribute levels, assign attribute levels to given probabilities or both. In any case, the data can be fitted to a specific probability functionality (most likely a normal curve).

At this point utilities can be calculated using the combined results of the MAUA and SPA questionnaires. These results can be used in several ways, each offering powerful insight into the way in which materials are selected. First of all, we can rank the materials according to their utility. Additionally, and as a special advantage of the utility method, the utility can indicate by how much a performance characteristic must change in order for the decision-maker to be just indifferent between any one alternative and another. With such information, it is possible to define engineering and design objectives in a fashion much more meaningfully, by directly taking into account the preferences of the target market.

A third form of study focuses on the analysis of the form of the generated utility function itself. The shape of the function, particularly its curvatures and inflections, reveal how the relative importance of individual characteristics change as different levels of importance are achieved, indicating critical decision thresholds.
For example, consider the following two figures. In each case, the figures present a contour map of a utility function for cost and tensile modulus. The contours show combinations of cost and modulus which yield the same utility value; these 'iso-utility' lines therefore are composed of combinations of cost and modulus which are equally preferred by the subject.

![Diagram](image)

**Figure 1:** Cost vs. Tensile Modulus Iso-Utility Map: Cost Dominant

In Figure 1, the iso-utility lines are almost vertical. This shape indicates that, over the range represented here, changes in modulus have a relatively small effect on the level of utility achieved, while changes in cost have a very large effect. Therefore, cost is relatively more important to this decision maker, and is likely to be the determining factor in materials selections, provided some minimum level of performance is achieved. Certainly, these curves indicate that he would be unwilling to pay a premium to achieve better than nominal performance.
In Figure 2, the shape of the iso-utility curves is more complex (and more typical). The slopes of the curves vary over the entire range of cost and modulus, suggesting that the relative importance of the attributes depends upon the levels available. Furthermore, note the bunching of the iso-utility curves in the vicinity of 10 million pounds per square inch (msi). This appearance suggests that, below 10 msi, increasing strength is far more important than reducing cost, while above 10 msi, the reverse is true.

Such insights are particularly valuable, not only in evaluating the competitive position of material alternatives, but also in speculating upon the effects of potential changes in material performance on competitiveness. Such evaluations can be used to establish research objectives or to devise material marketing strategies.

**Limitations**

While utility analysis offers new avenues in materials selection techniques, it does have a number of limitations. First, for materials selection problems involving more than six important characteristics, the interview process takes too long to be feasible for most situations. There are real limitations on the time one can expect to get from decision makers in these areas, and there are similar limitations on the time they can be expected to concentrate on a series of difficult questions.

The technique can thus be expensive. It is not only time consuming to develop and administer the questionnaire, but also to identify the individuals who actually select materials. These individuals are rarely so apparent that they can be picked out of an organizational chart, and a familiarity with the engineering practice and organizations of the industry being analyzed is a necessary part of the analysis.

Finally, the administration of the questionnaire requires an interviewer sensitive to the interviewees' reactions as well as to the needs of the analyst. There is a real skill which must be developed before the results of an interview can be reliably employed. A familiarity with the
engineering issues that the decision maker faces is vital to the development of a questionnaire comprising the give and take which is the hallmark of a good interview.

Materials Analysis Applications
To illustrate the wide range of uses to which MAUA can be applied, two analyses drawn from recent work will be discussed in the following sections. The first will present a straightforward application of MAUA to evaluating a set of available material alternatives, while the second will undertake a more speculative venture into estimating competitive pricing of a new material.

Case 1
Certain Attribute Levels:
Automobile Camshaft Materials [14]
In this study, material and processing alternatives for making camshafts were analyzed, focusing upon five process alternatives: nodular casting, steel forging, microalloy forging, a hybrid process (segmented camshaft) using a hollow steel tube with forged lobes held in place by hydraulic expansion of the tube, and the fully machined camshaft. While nodular cast camshafts are the predominant form used today, there are forces driving automakers to consider material and process alternatives. These forces are reduced weight, increased surface strength, increased stiffness, and, of course, reduced cost.

Based upon these concerns, an analysis of the competitive position of the five alternatives was undertaken using MAUA. Following an extensive literature review and discussions with camshaft designers, the attributes presented in the following table were chosen for detailed study:

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Typical (Cast)</th>
<th>Best</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Cost ($)</td>
<td>12</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Part Weight (lbs)</td>
<td>6</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Material Modulus (ksi)</td>
<td>21,000</td>
<td>40,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Compressive Yield Strength (ksi)</td>
<td>230</td>
<td>300</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 1: Attributes Analyzed for the Camshaft

Only physical attributes which could be traded off against one another or against cost were considered. By no means should these properties be considered exhaustive; rather, these were characteristics which merited the type of analysis that MAUA makes possible because there were indications that these characteristics could be traded off against one another. Other equally important characteristics were not included because simple "go/no go" materials selection criteria based on fixed performance targets had been established.

Responses indicated that, while the camshaft ought to meet strength specifications, designers do not seem to attach any value to exceeding those specifications. The prime design issue is increasing the stress carrying capacity of the lobes. The modulus is a key contributor to the stress carrying capacity of the cam lobes, through the Hertzian stress equation [15,16]. While this relationship suggests that optimal surface stress performance is a complex function of both
material modulus and compressive strength, subsequent analysis of designer preferences suggested that the individual characteristics also were accorded value individually, and they were thus assessed independently.

The performance of the five alternatives (under specific conditions - see reference 14 for more details) are presented below:

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cost (lbs)</th>
<th>Weight (lbs)</th>
<th>Modulus (ksi)</th>
<th>Compressive Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodular Casting</td>
<td>$10.71</td>
<td>6.0</td>
<td>21.0</td>
<td>230.0</td>
</tr>
<tr>
<td>Steel</td>
<td>$15.48</td>
<td>6.0</td>
<td>29.0</td>
<td>295.0</td>
</tr>
<tr>
<td>Microalloyed Steel</td>
<td>$13.64</td>
<td>6.0</td>
<td>29.0</td>
<td>295.0</td>
</tr>
<tr>
<td>Assembled</td>
<td>$15.70</td>
<td>3.4</td>
<td>29.0</td>
<td>295.0</td>
</tr>
<tr>
<td>Fully Machined</td>
<td>$17.57</td>
<td>6.0</td>
<td>29.0</td>
<td>295.0</td>
</tr>
</tbody>
</table>

Table 2: Matrix of Attributes for the Alternatives of Concern

The results of the utility analysis yielded the following ranking for the five alternatives:

```
Alternative                  Utility Ranking
Assembled                    1
Microalloy Steel Forged Camshafts 2
Steel Forged Camshafts       3
Nodular Cast Camshafts       4
Fully Machined Camshatf      5
```

Steel has a higher utility than nodular iron primarily because of its higher modulus and higher compressive strength. Although steel forgings are more expensive than castings, they still have a higher utility due to an overriding preference for high modulus and compressive strength. Apart from the enhanced modulus over the cast cams, the assembled camshaft also offers a reduction in weight. Thus, depending on the needs of the engine, it may be worthwhile to select this route, even though it is more expensive than the steel forging.
The importance of compressive strength is further illustrated in Figure 3, showing an iso-utility map in cost and compressive strength space (all other attributes held fixed). The notable feature of this figure is the fact that, over most of the domain plotted, cost is the dominant figure of merit, having the greatest influence upon utility. However, there is a clear inflection point in the vicinity of 220 ksi, indicating that 220 ksi is an important threshold of performance.

These results were essentially confirmed in follow-up discussions with automobile camshaft designers, who are definitely moving in the direction of higher performance materials for this application. The results strongly support the contention that forged camshafts, using either microalloy steel or powder forged steel, are going to become increasingly important in camshaft design in the next few years. Furthermore, the results suggest that cost improvement, through manufacturing innovations like near net shape processing, are generally of greater interest to these automobile part designers than major performance improvements.

This case shows how multi-attribute utility analysis can be used to analyze a complex material choice problem, where the performance of individual alternatives vary in a complex fashion. MAUA provides the analyst with a method for directly assessing the value of varying levels of performance and relating this value to the overall value of alternatives with large differences in performance in several dimensions. Beyond this ability, analysis of the utility function itself yields insight into elements of the designer's thinking process by revealing critical levels of performance which have particular value to the designer. This information can be used to target particular markets with new material offerings as well as to direct material development efforts.

Figure 3: Cost vs. Compressive Strength: Camshaft Case Study
CASE 2
Uncertain Attribute Levels:
Aircraft Gas Turbine Engine Exhaust Duct Materials [17]:

In this study the added dimension of uncertainty associated with the attribute levels of new technologies exists. Two of the materials alternatives, the ceramic fiber composites made by different fabrication techniques have a great deal of uncertainty associated with their actual performance characteristics. Accordingly, SPA was used in addition to MAUA in analyzing this case.

After initial evaluation of materials for this application, potential materials/technologies were narrowed down to the currently used superalloys, and ceramic matrix composites made by two processing techniques. The case study compared the competitiveness of investment cast superalloys, SiC/SiC composites made by a slurry infiltration technique and SiC/SiC composites made by a chemical vapor infiltration.

In addition to identifying materials possibilities, relevant attributes were also identified. Consultations with engine designers led to a list of six important considerations; maximum operating temperature, strength, toughness, coefficient of thermal expansion mismatch at the attachment site, density and cost. Of course, design of this component requires consideration of a much larger set of engineering criteria. However, most of these attributes are evaluated on a "Go/No Go," or binary, basis. Unlike the remaining six attributes, decision makers evaluating alternatives on the basis of these binary attributes essentially assure themselves that minimum targets are met, with no particular benefit associated with exceeding those minimum targets. On the other hand, the preliminary analysis suggested that designers were willing to trade-off the remaining six attributes against one another. For each of the attributes, acceptable ranges of values were determined and are given below. Accordingly, MAUA results are only applicable within these ranges.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Units</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Operating Temperature</td>
<td>°C</td>
<td>750</td>
<td>1,500</td>
</tr>
<tr>
<td>2. Strength</td>
<td>ksi</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>3. Toughness</td>
<td>MPa m</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>4. CTE Mismatch</td>
<td>10^-6 in/in/°F</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>5. Density</td>
<td>g/cm³</td>
<td>1.8</td>
<td>9</td>
</tr>
<tr>
<td>6. Cost</td>
<td>$</td>
<td>1,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Table 3: Attribute Ranges for the Exhaust Duct

Five engine designers were then interviewed. Using the multi-attribute utility analysis technique, the relative importance of the six attributes was determined for each of the alternatives for each engine designer. In addition, attribute levels for each of the alternatives were obtained and are given below.
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Investment Cast Superalloy</th>
<th>Slurry Infiltrated SiC/SiC</th>
<th>Chemical Vapor Infiltrated SiC/SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Operating Temperature (°C)</td>
<td>800</td>
<td>1,100</td>
<td>1,400</td>
</tr>
<tr>
<td>2. Strength (ksi)</td>
<td>100</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>3. Toughness (MPa (\text{m}^3))</td>
<td>60</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>4. CTE Mismatch (10(^{-6})in/in/^\circ F)</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>5. Density (g/cm(^3))</td>
<td>8.9</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>6. Cost ($)</td>
<td>1,000</td>
<td>4,635</td>
<td>9,291</td>
</tr>
</tbody>
</table>

Table 4: Attribute Levels for the Materials Alternatives for Exhaust Ducts

Unfortunately, attribute levels for the two ceramic matrix composite exhaust ducts were difficult to determine in practice, since these materials are currently not being used in the production of this component. Attribute levels supplied by developers of the composites were used, but there was some uncertainty as to whether these would accurately reflect the material's performance in the application. Consequently, the subjective probability assessment technique was used to adjust for the doubts which engine designers had concerning the accuracy of the attribute levels for the ceramic matrix composites. In this case, three engineers participated and were asked about the credibility of the values given for three of the attributes for the ceramic matrix composites. Only maximum operating temperature, strength and toughness were considered. The coefficient of thermal expansion and the density of the material were assumed to be easily measurable and thus there was no uncertainty about these attributes. Cost would be a fixed amount given in a contract to purchase the component, and thus there was no uncertainty in this case either. Probability distributions for the remaining three attributes for each of the ceramic matrix composite technologies were determined for each of the three engine designers. These distributions were used in place of the fixed, uncertain attribute level, and new utility values were obtained. The results are given in Figure 4. See reference 17 for a complete treatment of this case study.
Figure 4: Utility of the Materials Alternatives

Summary

The utility analysis approach to materials selection yields results which cannot be matched by any of the currently available techniques. By constructing a formal representation of a materials decision maker's preferences, it is possible to obtain both accurate and flexible representations of the materials selection process.

The analysis is neither sensitive to arbitrary choices of normalizing constants, nor limited to linear representations of materials preference, as the other techniques assume. Furthermore, the observed preference structure can be applied not only to the problem of assessing the relative suitability of materials for a particular application, but also to the question of the degree of difference between alternatives, the relative importance of performance characteristics, and the way in which various performance characteristics are factored into the materials selection decision.

In addition, through the use of subjective probability assessment, uncertainties associated with new, unproven technologies can be easily accommodated. This allows one to investigate not only
the trade-offs between attributes, but also the likelihood of new technologies achieving predicted performance levels. This information can be a significant factor when deciding the direction of research programs involving new technologies.

The advantages of the utility analysis approach do come at a price: it places some burden of time and energy on the engineers and decision makers. Much of this can be alleviated, however, through careful application of the underlying theory as well as the use of interactive computer programs for assessing utility and performing the analysis.